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RESEARCH AND DEVELOPMENT (R&D) SUPPORT**

Delivery Order 0011: Advanced Propulsion Fuels R&D

**Subtask: Evaluation of 50/50 Hydroprocessed Renewable Jet Fuel and JP8 in the
Ford 6.7L High-Pressure Common Rail Design Engine**

Douglas M. Yost and Adam C. Brandt

Southwest Research Institute (SwRI®)

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Interim Report

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JAMES T. EDWARDS
Program Manager
Fuels & Energy Branch
Turbine Engine Division

//Signature//

MIGUEL A. MALDONADO, Chief
Fuels & Energy Branch
Turbine Engine Division
Aerospace Systems Directorate

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PREFACE

This report was prepared for the Universal Technology Corporation (UTC), 1270 North Fairfield Road, Dayton, Ohio, 45432-2600 under Contract Number 11-S590-0011-02-C7 with the Air Force Research Laboratory's Aerospace Systems Directorate (AFRL/RQ). Mrs. Michele Puterbaugh (Contractor, Universal Technology Corporation) was the project manager for this effort. Mr. James Klein, (Subcontractor, Klein Consulting LLC), was the technical leader in support of Dr. James T. Edwards, Senior Scientist, of the Fuels & Energy Branch (AFRL/RQPF), Power Division, Aerospace Systems Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio. The research reported herein was performed by Southwest Research Institute, 6220 Culebra Road, San Antonio, TX and covers the period of October 01, 2010 through November 09, 2012. This effort was funded by the Air Force Research Laboratory.

1.0 EXECUTIVE SUMMARY

Commercial Off-The-Shelf (COTS) diesel engines are available to the U.S. Military that employ High Pressure Common Rail (HPCR) fuel injection systems. Overall performance and endurance of these HPCR systems has the potential to vary with use of military or alternative fuels due to critical chemical and physical property differences compared to standard diesel fuels. Of the critical property differences of military fuels, changes in fuel viscosity and lubricity are of particular interest. Many modern HPCR systems utilize fuel lubricated high pressure pumps, and can generate upwards of 2000bar fuel rail pressures placing large demands on the fuel to adequately lubricate and protect internal components.

To understand critical fuel related impacts, performance and endurance testing was conducted using a fired engine equipped with a modern fuel lubricated HPCR fuel system with a 50%/50% volumetric blend of JP-8 and Hydroprocessed Renewable Jet (HRJ), also known as Hydroprocessed Esters and Fatty Acids (HEFA) treated with 9ppm of a QPL-25017 additive. Testing was completed using a Ford 6.7L V8 turbocharged diesel engine. The engine used was tested in its "export" configuration, which does not utilize Exhaust Gas Recirculation (EGR) or exhaust after-treatment systems. Testing was completed following a double-duration modified version of the U.S. Army 210-hr Tactical Wheeled Vehicle Cycle (TWVC).

At the completion of each test, fuel injection pumps and injectors were removed and disassembled for inspection and comparison. Component inspections for the JP-8/HRJ blend were compared to component conditions from previous work. Engine power curves and emissions were taken at the start, middle, and end of testing, and used to document any engine performance degradation incurred over the test duration.

The engine with JP-8/HRJ fuel was successfully operated over the test duration without experiencing any unusual fuel related operational conditions or hardware failures. At the minimum lubricity enhancing treat rate, the tested JP-8/HRJ fuel provided adequate component protection and system performance compared to an Ultra Low Sulfur Diesel (ULSD) baseline test. Post-test fuel injection system inspection found tested components to be in similar condition for all fuels tested. Results from testing support the compatibility of the fuel lubricated HPCR fuel system utilized on the Ford 6.7L with a military specified JP-8/HRJ fuel blend.

2.0 INTRODUCTION

A large number of current Commercial Off-The-Shelf (COTS) diesel engines available to the U.S. Military employ High Pressure Common Rail (HPCR) fuel injection systems. Life cycle performance and endurance of these HPCR fuel systems have the potential to be impacted by critical chemical and physical property differences between military specification fuels and standard diesel fuels. Although these critical factors can include many different properties, primary concerns lie with the fuels lubricity and viscosity, as these can have major interactions with fuel system hardware. Many HPCR fuel injection pumps (FIP) are fuel lubricated and depend on lubricity specific fuel properties to provide adequate hardware protection during use. Modern HPCR FIP's can generate upwards of 2000bar fuel pressure which can result in tremendous loading on internal components, thus placing further demands on the fuel to protect fuel system hardware. In addition, fuel viscosity effects can dramatically alter internal leakage and filling rates which can change the overall efficiency of the fuel injection system, and potentially impact engine out performance. With the large in-flux of HPCR technology into the diesel engine market, many questions have arisen on whether modern HPCR systems will maintain adequate performance and durability using current and future (synthetic based) military fuels.

2.1 Objective

This test objective was to determine the performance and endurance of a modern high pressure common rail diesel fuel injection system when operated on a 50/50% volumetric blend of JP-8 and Hydroprocessed Renewable Jet (HRJ) fuel. Testing was completed following a modified double-length version of the 210-hour Tactical Wheeled Vehicle Cycle engine endurance test cycle (CRC Report No. 406, Development of Military Fuel/Lubricant/Engine Compatibility Test) (1). Evaluations of performance and durability included, but were not limited to, fuel system hardware interactions, engine performance changes, and engine out emissions evaluations. This work was completed in support of Project 08.16246, Advanced Propulsion Fuels Research and Development. Comparisons of engine performance and fuel injection component conditions for the HRJ blend are being made to the baseline test fuels evaluated and reported in: *"Evaluation of Military Fuels using a Ford 6.7L Powerstroke Diesel Engine"*, Interim Report TFLRF No. 415, August 2011, ADA560574.

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

3.1 Test Engine

The Ford 6.7L diesel engine was chosen for testing as a representative engine utilizing modern high pressure common rail fuel injection technology. The Ford 6.7L engine is a V8, direct injected, turbo-charged, intercooled engine, which employs a fuel lubricated high pressure common rail injection pump and piezo-electric fuel injectors. The 6.7L engine used for testing was produced by Ford as an “export” version, intended for sale outside of U.S borders or to military forces. In the export configuration, the engine does not come equipped with engine exhaust after-treatment systems or exhaust gas recirculation (EGR) systems. The 6.7L export version engine is rated at approximately 320hp (238kW) at 2800rpm, and produces approximately 700 lb-ft (950 N-m) of torque at 1800rpm when using diesel fuel. Figure 1 below shows the 6.7L engine test installation. The test engine was purchased new directly from Ford Motor Company for testing, and all new fuel system hardware present on the engine was used for testing.



Figure 1. Ford 6.7L Engine Test Stand Installation

3.2 Fuel System Description

Fuel injection system on the Ford 6.7L engine utilizes a fuel lubricated high pressure pump supplying two pressure controlled fuel rails and 8 piezo-electric actuated fuel injectors. The Fuel Injection Pump (FIP) is mounted at the front of the engine valley and gear driven at 1:1 engine speed. The FIP is a two cylinder design and utilizes a two lobe cam to provide four pulses per revolution. The FIP is timed to the crankshaft and camshaft orientation to optimize pressure pulses within the fuel system during operation. Fuel management is controlled by the Powertrain

Control Module (PCM) through the use of a FIP mounted Volume Control Valve (VCV) and a fuel rail mounted Pressure Control Valve (PCV). The engine primarily operates in VCV mode, in which the VCV valve regulates the amount of fuel entering the high pressure portion of the FIP based on engine demands. The PCV allows the PCM to trim the fuel rail pressure as needed, to regulate total fuel rail pressure and adjust as engine demands change. This design is primarily utilized to increase the efficiency of the fuel injection system, as only the fuel required for operation is compressed by the pump and sent to the fuel rails. Figure 2 below shows the Ford 6.7L fuel injection pump, fuel pressure rail, and fuel injector. The VCV is located atop the center of the FIP between the two high pressure cylinder head assemblies. The PCV valve is located at the left end of the high pressure fuel rail as seen below.

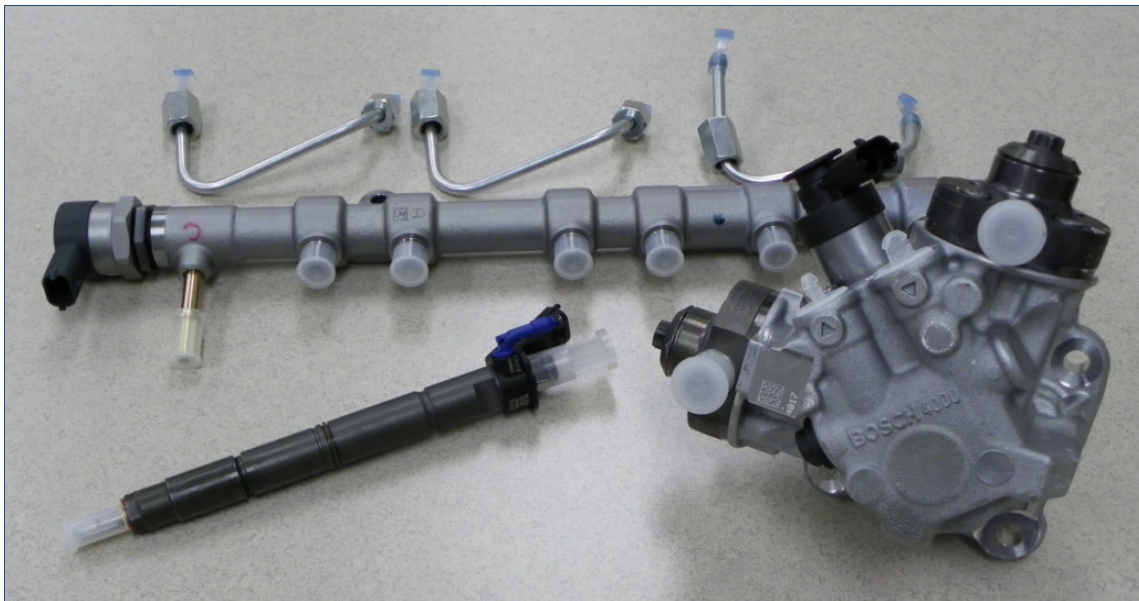


Figure 2. Ford 6.7L Fuel Injection Pump, Rail, & Injector

The high pressure portion of the FIP consists of a high pressure plunger and barrel assembly that is actuated by roller follower assembly driven from the FIP camshaft. Regulated fuel from the VCV valve is drawn into the barrel assembly on the downward stroke, and then compressed and brought to the specified rail pressure upon plunger ascent. High pressure fuel exits the barrel assembly through a spring loaded check ball into high pressure fuel lines that supply the fuel rails. Figure 3 below shows the orientation of high pressure pumping assembly. Critical wear points for these components can include: roller and shoe surface wear, scuffing on the follower and follower bore surfaces, plunger and barrel surface wear and scuffing, wear between high pressure plunger head and shoe assembly, as well as fuel check valve and seat wear.



Figure 3. Camshaft Follower & High Pressure Plunger & Barrel Assy

Figure 4 on the following page shows a parts break-out of the fuel injector. The fuel injector is a piezo-electric actuated unit that acts against one piston (upper) of a hydraulic coupler (Figure 5) that is filled with fuel from the low pressure lift pump portion of the fuel system. The hydraulic coupler translates the small linear movement of the piezo-stack to a larger movement by the difference in piston diameters within the hydraulic coupler. The second piston (lower) of the hydraulic coupler acts against the injector control valve (Figure 6), that regulates the pressure on the top of the injector needle controlling the needle lift. When the control valve is forced down, the high pressure fuel passage is blocked lowering the pressure acting on the top of the needle and allowing the high pressure fuel acting below to lift the needle and inject fuel into the combustion chamber. Figure 5 and Figure 6 show larger views of the hydraulic coupler and control valve assembly. Critical wear points for these components can include: control valve and seat wear, wear and scuffing on needle surface from guide, needle seat wear, and deposit formation on nozzle.

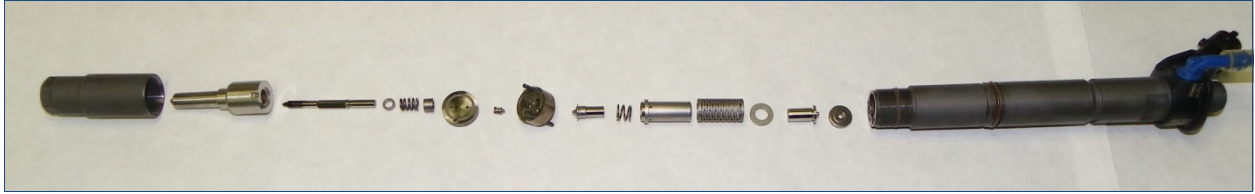


Figure 4. Fuel Injector Component Break-Out

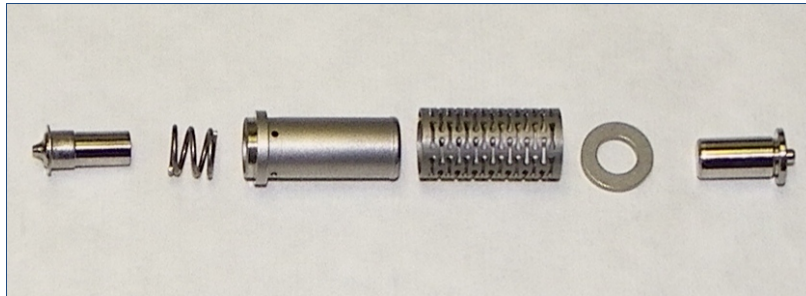


Figure 5. Fuel Injector Hydraulic Coupler



Figure 6. Fuel Injector Control Value Assembly

3.3 Test Stand Configuration

The engine was mounted in a test stand specifically configured for Ford 6.7L engine testing. The following list outlines the general test stand set-up in regards to the engine installation, and ancillary equipment used during testing.

- The engine was fully instrumented to monitor various engine parameters, temperatures, and pressures throughout testing. A SwRI developed data acquisition and controls system (PRISM) was used to display and log real time engine data during testing.
- Engine speed was controlled by an absorption eddy current dynamometer. Engine load was controlled using a PRISM controller and actuator to manipulate the drive-by-wire throttle pedal attached to the engine's dyno harness.

- Coolant temperature (engine water jacket and secondary coolant loop) was controlled by PRISM using the building supplied process water and appropriately sized heat exchangers in place of the engine's radiators.
- The engine was supplied with fuel by using a "day tank" at ambient temperature and pressure conditions. The day tank allows the engine to feed and return fuel as required during operation. Fuel in the day tank is kept at a constant level by a secondary fuel pump that replenishes the tank supply as necessary from bulk fuel storage. The make-up fuel flow rate into the day tank is the resulting fuel used by the engine, and is measured by a MicroMotion Coriolis flow meter and logged with PRISM as the engine fuel consumption rate.
- Fuel from the day tank was supplied to the engines diesel fuel condition module (DFCM) at ambient temperature and pressure. The DFCM houses the primary fuel filter and low pressure lift pump for the engine. The DFCM also contains a temperature controlled recirculation device that re-routes engine return fuel to the engine supply until a desired fuel temperature is met. To not interfere with the DFCM operation, the inlet fuel to the DFCM was not conditioned in any way.
- Inlet air was drawn in at ambient conditions from the test cell through a radiator core into the engine air box. The radiator core is supplied building process water to prevent extreme heat buildup in the test cell from elevating inlet air temperatures.
- Engine exhaust is drawn from the engine by the buildings exhaust handling system and discharged outside to the atmosphere. A butterfly valve was used to regulate engine exhaust backpressure to the Ford recommended 1 lpsi specification.
- Emissions were directly sampled from an exhaust probe installed between the engine and exhaust system backpressure valve. Emissions were measured using a Horiba MEXA-1600D Motor Exhaust Gas Analyzer. Exhaust sample handling was carried out by the Horiba systems heated filter and line routed into the emission bench sample conditioning unit.
- Crankcase blow-by gasses were recirculated into the turbo compressor inlet via the factory blow-by control devices.
- The engine was lubricated with commercially available full synthetic CJ-4 SAE 5W-40 engine oil per Ford specifications for heavy duty applications.
- Used oil samples were collected from the engine daily to monitor engine and oil condition, and to determine oil change intervals needed during testing.

3.4 Engine Run-In

Prior to testing, the engine was run-in following the Ford specified engine run-in procedure. Table 1 on the following page outlines the Ford recommended engine run-in procedure.

Table 1. Ford Recommended Run-In Procedure

Step	Duration	Speed	Load	
		[rpm]	[lb-ft]	[N-m]
1	0:05	650	0	
2	0:30	1000	72	97
3	0:30	1200	103	140
4	0:30	1400	141	191
5	0:30	1500	162	219
6	0:30	1600	184	249
7	0:30	1700	208	282
8	0:30	1800	233	316
9	0:30	2000	287	390
10	0:30	2200	348	472
11	0:30	2400	414	561
12	0:30	2500	449	609
13	0:30	2600	486	659
14	0:30	2700	524	710
15	0:30	2800	563	764

(Duration in hours: minutes)

3.5 Pre and Post Test Engine Performance Checks

Before and after testing, engine power curves were completed at varying speeds and loads to determine pre-test engine performance. Engine performance was documented at engine speeds of 1400, 1800, 2200, 2400, and 2800rpm, with load intervals of 25%, 50%, 75%, and 100% of full load. Power curves were completed at both ambient (95°F) and desert condition (120°F) inlet fuel temperatures. Exhaust gas emissions were sampled at each point on the curve to document engine out emissions. Power curve plots can be seen in the Engine Performance Curves section.

3.6 Test Cycle

The test cycle followed during fuel system evaluations was a modified version of the 210-hour Tactical Wheeled Vehicle cycle as outlined in CRC Report No. 406, Development of Military Fuel/Lubricant/Engine Compatibility Test. A double length cycle was run to increase testing hours to 420-hours total. Modifications were made to the daily testing cycle to accelerate the testing schedule. The primary modification was the reduction of engine soak time from 10-hours to 3-hours. The engine soak period in the test cycle was originally included for engine lubricant testing, and added no benefit for fuel compatibility testing. Total modified daily runtime was 21-hours per day, 15-hours at rated speed and load and 6-hours at idle, followed by a 3-hour engine soak. To keep the modified test cycle rated to idle testing hours consistent with the standard 210-hour Tactical Wheeled Vehicle Cycle, the following daily operating arrangement was derived. The engine completed 6 cycles, each consisting of 2-hour 10-minute at rated speed followed by a 1-hour idle step. After the 6 cycles were completed, an additional 2-hour rated segment was conducted followed by the 3-hour soak. Engine coolant temperatures were maintained at Ford specifications to ensure engine integrity throughout the test. Engine coolant

utilized was a 50/50 blend of ethylene glycol antifreeze and de-ionized water. Engine operating parameters were controlled as specified in Table 2 below.

Table 2. Test Cycle Operation Parameters

Parameter	Rated Speed	Idle
Engine Speed	2800 +/- 25	NC
High Temp Coolant Loop	203 +/- 3	NC
Low Temp Coolant Loop	100 +/- 3	NC
Oil Sump	NC	NC
*NC = not controlled		

(Note – Engine idle speed was controlled by PCM at approximately 600rpm. Temperature controllers remained at rated speed set points for idle conditions, but were not met due to lack of heat generation in the coolant system. Temperatures were allowed to reach their natural steady state value during idle testing steps. Engine oil cooler plumbing was integral to the engine water jacket, thus not directly controlled. Oil temperatures were allowed to meet their own steady state temperature based on water jacket temperature and engine load/speed throughout testing.)

3.7 Oil Sampling

Four ounces of engine oil was sampled every 21-hours (daily) for used oil analysis. Used oil analysis consisted of the following tests as seen in Table 3 below. Engine oil changes were to be performed on the engine based on used oil condition. In this case the lubricant was changed at the 210-hour interval.

Used oil analysis results can be seen in the engine oil analysis and engine oil analysis trends section of the report.

Engine oil level was checked daily, and replenished as needed to restore oil level to full mark. This process occurred after the completion of the 3-hour soak prior to restarting testing the next day.

Table 3. Used Oil Analysis Procedures

Daily Used Oil Analysis		
ASTM	D4739	Total Base Number
ASTM	D664	Total Acid Number
ASTM	D445	Kinematic Viscosity @ 100°C
ASTM	API Gravity	API Gravity
ASTM	D4052	Density
ASTM	TGA SOOT	TGA Soot
ASTM	E168	Oxidation
ASTM	E168	Nitration
ASTM	D5185	Wear Metals by ICP

3.8 Test Fuel

The test fuel was a 50/50 blend of JP-8 and Hydroprocessed Renewable Jet (HRJ). The JP-8 was blended at location from commercially available Jet A. JP-8 is normally made by blending military additives into Jet A-1, a lower freeze point specification than Jet A. The Jet A used for this testing would also have met the Jet A-1 specification because the freeze point specification was met. The blend consisted of a true 50/50 volumetric blend. Since the primary focus of testing was fuel lubricity compatibility, only the lubricity enhancer/corrosion inhibitor additive was blended into the Jet A and HRJ base fuels. The remaining two additives typically found in JP-8 have little impact on fuel lubricity levels and fuel system durability. The lubricity enhancer used was Innospec Fuel Specialties DCI-4A. Per QPL-25017, the minimum effective treat rate of DCI-4A required an additive concentration of 9ppm in the final fuel blend. In an effort to determine fuel system impact in a “worst case” scenario, the test fuel was treated only at the minimum effective treat rate regardless of the resulting lubricity level achieved. After the test fuel was additized and blended, fuel samples were collected to determine critical chemical and physical properties of the fuel for reporting. Table 4 summarizes the critical properties of the tested 50/50 JP-8/HRJ. Table 5 shows the certificate of analysis (COA) for the Jet A as received. Table 6 shows the chemical and physical analysis of the neat HRJ as received prior to blending.

Table 4. Test Fuel Chemical & Physical Analysis

Property	Units	ASTM Method	Results
Density @15°C	g/mL	D4052	0.777
Specific Gravity @15°C		D4052	0.778
API Gravity @15°C		D4052	50.4
Flashpoint	°F	D56	116
	°C	D93	49.5
	°F	D3828	49
Kinematic Viscosity @-20°C	cSt	D445	4.01
Kinematic Viscosity @40°C	cSt	D445	1.29
Hydrocarbon Content			
Carbon	wt%	D5291	85.18
Hydrogen	wt%		14.42
Calculated Cetane Index	CCI	D976	52.7
Calculated Cetane Index, Four Variable	CCI	D4737	56.1
Cetane Number	CN	D613	46.3
Ignition Quality Tester™	DCN	D6890-11	52.6
Heat of Combustion (Gross)	BTU/lb	D240	19992.4
Total Acid Number	mg KOH/g	D3242	0.016
Hydrocarbon Type			
Aromatics	%mass	D5186	10
Hydrocarbon Type			
Aromatics	%vol	D1319	7.5
Olefins			0.9
Saturates			91.6
Sulfur	ppm	D5453	6.8
Nitrogen	wt%	D3228	<0.030
HFRR	mm	D6079	0.7
BOCLE	mm	D5001	0.61
Bulk Modulus @30°C	psi	by Speed of Sound	173820
Distillation			
IBP	°C	D86	159.6
10%			173.4
20%			178.4
50%			196.6
90%			238.7
End Pt			255.6

Table 5. Valero Jet-A Certificate of Analysis (COA)

01/02/2011 17:11 8303938101

ALCOR PETROLAB LLP



20 Laboratory Road, Floresville, Texas 78114 Telephone 830-216-3113 www.alcorpetrolab.com

NuStar
San Antonio Products Terminal
P. O. Box 241017
San Antonio, Texas 78224-1017

January 2, 2011

Sample Type: Jet A
Tank Number.: 103
nt @ 1007 01/02/11 pu @ 1330 01/02/11

Sample Date: 01/02/11
Sample Time: 1330

<u>Volatility</u>	<u>Method</u>	<u>Specification</u>	<u>Result</u>
Initial Boiling Point (°F)	D 86		333.3
Distillation 10% Rec (°F)		400 max	345.4
Distillation 50% Rec (°F)		Report	365.9
Distillation 90% Rec (°F)		Report	412.5
Distillation 95% Rec (°F)		Report	431.4
Distillation Final BP (°F)		572 max	475.5
Distillation Recovery (vol %)			98.2
Distillation Residue (vol %)		1.5 max	0.7
Distillation Loss (vol %)		1.5 max	1.1
Flash Point, Tag Closed (°F)	D 56	100 min	127.0
API Gravity @ 60 (°F)	D 1298	37.0 / 51.0	45.0
Cetane Index	D 4737	40.0 min	39.7
Particulate Matter Mgs/Gal	D 2276	3.0 max	0.8
Sulfur Wt %	D 7220	0.30 max	0.0005
Copper Strip	D130	No. 1 max	1A
Existent Gum Mgs / 100 Mls.	D381	7 max	<1.0
<u>Fluidity</u>			
Freezing Point (°F)	D 2386	-41.0 max	-82.3
<u>Contaminants</u>			
Color (Saybolt)	D 156	+15 min	+30
Appearance	D4176	clear/bright pass/fail	Pass
Water Reaction: Change	D 1094	2.0 max	0
Water Reaction: Interface Rating	D 1094	2 max	1
Water Reaction: Separation Rating	D 1094	2 max	1
MSEP	D 3948	85 min	98

This Product Conforms to ASTM D1655 for the Above Tests: XX YES ___ NO

Reviewed and submitted by:

Chris Taylor CEO/PL
Chris Taylor CEO

Report Number: P010211A



4

Table 6. Chemical & Physical Analysis of HRJ

AFPET LABORATORY REPORT
HQ AFPET/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

AMENDED REPORT

Lab Report No: 2010LA23904001

Protocol: FU-AVI-0019

Cust Sample No: 6308

Date Sampled: 03/12/2010

Date Received: 03/12/2010

Date Reported: 03/23/2010

Sample Submitter:

AFRL/RZPF

1790 Loop Road N

Bldg 490

WPAFB, OH 45433

Reason for Submission: AFRL Research

Product: Aviation Turbine Fuel, Kerosene

Specification: MIL-DTL-83133F Grade:JP-8

Qty Submitted: 2 gal

Method	Test	Min	Max	Result
ASTM D 2622 - 08	Sulfur (ppm)			<3
ASTM D 445 - 09	Viscosity @ 90°C (cSt)	Report Only		0.75
ASTM D 4052 - 09	Density @ 40°C (g/cm³)	Report Only		0.739
ASTM D 4052 - 09	Density @ 90°C (g/cm³)	Report Only		0.702
MIL-STD-3004A(1)	Appearance	Report Only		Pass
ASTM D 6045 - 09	Color, Saybolt	Report Only		+30
ASTM D 3242 - 08	Total Acid Number (mg KOH/g)	Report Only		0.002
ASTM D 1319 - 08	Aromatics (% vol)	Report Only		0.4
ASTM D 3227 - 04a	Mercaptan Sulfur (% mass)	Report Only		0.000
ASTM D 86 - 09	Distillation			
	Initial Boiling Point (°C)	Report Only		165
	10% Recovered (°C)	Report Only		179
	20% Recovered (°C)	Report Only		185
	50% Recovered (°C)	Report Only		210
	90% Recovered (°C)	Report Only		243
	End Point (°C)	Report Only		255
	Residue (% vol)	Report Only		1.2
	Loss (% vol)	Report Only		0.8
ASTM D 93 - 09	Flash Point (°C)	Report Only		55
ASTM D 4052 - 09	API Gravity @ 60°F	Report Only		55.1
ASTM D 4052 - 09	Density @ 15°C (kg/L)	Report Only		0.758
ASTM D 5972 - 05e1	Freezing Point (°C)	Report Only		-62
ASTM D 445 - 09	Viscosity @ -20°C (mm²/s)	Report Only		5.3
ASTM D 3338 - 08	Net Heat of Combustion (MJ/kg)	Report Only		44.1
ASTM D 976 - 06	Cetane Index, Calculated	Report Only		67
ASTM D 3343 - 05	Hydrogen Content (% mass)	Report Only		15.3
ASTM D 1322 - 08	Smoke Point (mm)	Report Only		>40.0
ASTM D 130 - 04	Copper Strip Corrosion (2 h @ 100°C)	Report Only		1a
ASTM D 3241 - 09	Thermal Stability @ 260°C			
	Change in Pressure (mmHg)	Report Only		0
	Tube Deposit Rating, Visual	Report Only		1
ASTM D 381 - 04	Existent Gum (mg/100 mL)	Report Only		<1
ASTM D 5452 - 08	Particulate Matter (mg/L)	Report Only		0.3
MIL-DTL-83133F	Filtration Time (min)	Report Only		3
ASTM D 1094 - 07	Water Reaction Interface Rating	Report Only		1
ASTM D 3948 - 08	WSIM	Report Only		96
ASTM D 5006 - 03	FSII (% vol)	Report Only		0.00
ASTM D 2624 - 09	Conductivity (pS/m)	Report Only		53
ASTM D 5001 - 08	Lubricity Test (BOCLE) Wear Scar (mm)	Report Only		0.76
ASTM D 4809 - 09a	Net Heat of Combustion (MJ/kg)	Report Only		44.5
ASTM D 1319 - 08	Olefins (% vol)	Report Only		0.4
MIL-DTL-83133F	Workmanship	Report Only		Pass

4.0 RESULTS AND DISCUSSION

4.1 Endurance Test Cycle Results

The following information summarizes the results of the engine fuel system endurance tests. Data includes: engine operating summary, power curve analysis, engine out emissions, used oil analysis, post test component inspection, post test component photos, and listing of any problem areas or anomalies experienced during testing.

4.1.1 Engine Operating Conditions Summary

Table 7 is a summary of the engine operating conditions averaged over the test duration.

Table 7. Engine Operating Condition Summary

Parameter:	Units:	Rated Conditions (2800 RPM)		Idle Conditions (600 RPM)	
		Average	Std. Dev.	Average	Std. Dev.
Engine Speed	RPM	2800.04	1.94	601.61	2.89
Torque*	ft*lb	580.06	9.16	39.29	2.09
Fuel Flow	lb/hr	125.81	5.14	1.64	0.52
Power*	bhp	309.25	4.89	4.50	0.25
BSFC*	lb/bhp*hr	0.407	0.017	0.367	0.126
Temperatures:					
High Temperature Loop Coolant In	°F	184.41	0.36	182.91	7.96
High Temperature Loop Coolant Out	°F	202.99	0.25	185.82	8.16
Low Temperature Loop Coolant In	°F	100.28	1.27	96.07	3.76
Low Temperature Loop Coolant Out	°F	131.98	2.66	95.89	3.88
Oil Sump	°F	233.35	1.03	188.43	8.47
Fuel In	°F	89.27	5.65	85.44	6.25
Fuel Pump Drain	°F	107.77	6.34	91.75	6.19
Fuel Return	°F	101.97	3.27	93.07	4.82
Intake Air Before Compressor	°F	81.92	2.48	83.19	3.04
Intake Air After Compressor	°F	343.48	30.33	99.09	3.63
Intake Air After Charge Cooler	°F	108.26	1.14	96.24	4.00
Cylinder 1 Exhaust	°F	1424.76	17.51	273.30	13.11
Cylinder 2 Exhaust	°F	1342.88	18.39	270.87	10.75
Cylinder 3 Exhaust	°F	1389.40	21.00	278.12	9.35
Cylinder 4 Exhaust	°F	1411.94	36.50	277.95	8.77
Cylinder 5 Exhaust	°F	1383.12	18.84	259.31	14.95
Cylinder 6 Exhaust	°F	1414.86	24.43	291.90	11.62
Cylinder 7 Exhaust	°F	1401.03	26.33	274.86	9.87
Cylinder 8 Exhaust	°F	1371.72	31.72	270.25	8.85
Exhaust, Left Manifold Exit	°F	1375.19	29.50	252.04	15.02
Exhaust, Right Manifold Exit	°F	1405.98	26.34	247.85	9.66
Exhaust After Turbo	°F	1153.61	26.90	232.86	13.98
Pressures:					
Oil Galley	psi	58.48	0.41	29.88	1.48
Ambient Pressure	psiA	14.25	0.05	14.24	0.05
Intake Restriction	psi	0.52	0.03	-0.03	0.00
Exhaust Restriction	psi	10.40	0.24	-0.06	0.04
Boost Pressure	psi	19.36	0.81	0.41	0.04
Fuel Rail Pressure	psi	19366.50	26.07	3980.15	26.00

* Non-corrected Values

4.1.2 Engine Performance Curves

The plots below show the pre and post test engine power curves. Figure 7 reveals the pre, mid, and post test composite full load power curve comparisons for both fuel temperatures. After 420-hours of operation on the JP-8/HRJ fuel, the engine max power had decreased by 5.9% at ambient fuel temperature and 4.6% at elevated fuel temperature. The power reduction at the mid-test, or 210-hours, was consistent with the other fuels run in the 6.7L engine for 210-hours. Table 8 shows the power deviations seen with ULSD and JP-8 fuels at 210-hours of operation on the same test cycle. The power reduction seen appears to be due to reduced fuel delivery at full load.

Table 8. Power Deviations of Ford 6.7 L Engine from Test Fuel Durability Cycle

Fuel	Durability Test Fuel Temperature, °F (°C)	Test Duration, Hours	Power Curve Fuel Temperature, °F	Power Reduction after Test Duration, %
ULSD	90 (32)	210	95	1.8
			120	1.9
JP-8	90 (32)	210	95	2.6
			120	3.0
50/50 HRJ/JP-8	90 (32)	210	95	3.1
			120	2.0
50/50 HRJ/JP-8	90 (32)	420	95	5.9
			120	4.6

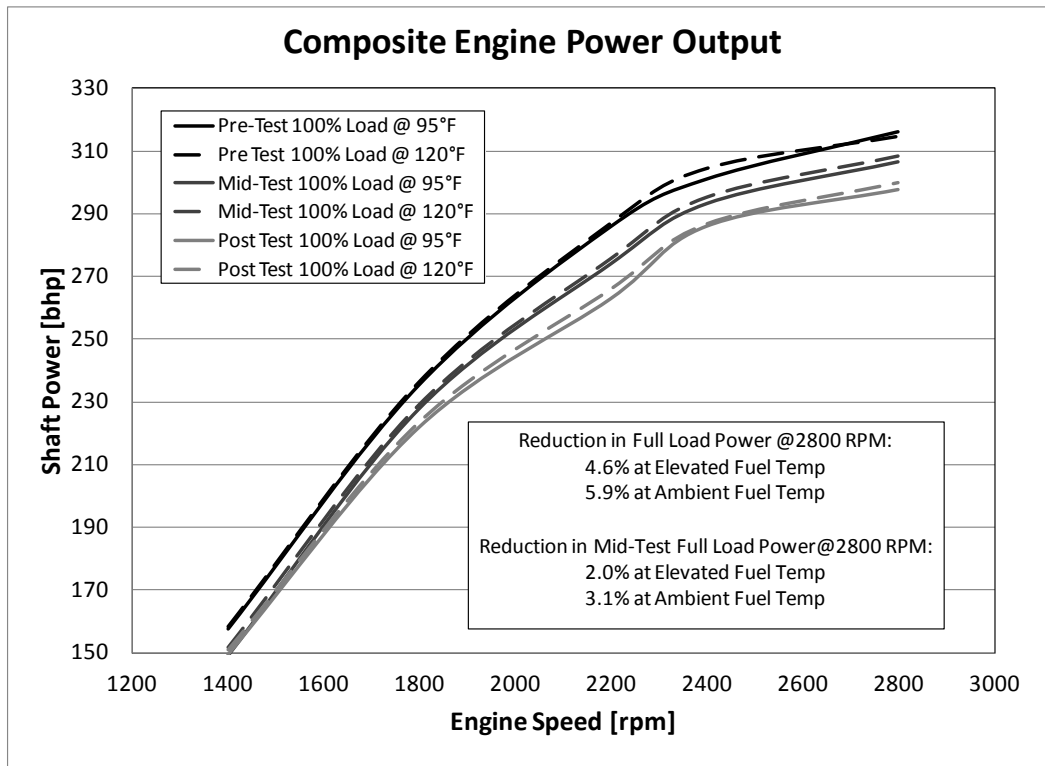


Figure 7. Composite Engine Power Output

Figure 8, Figure 10, and Figure 12 show the engine power output performance maps generated with the JP-8/HRJ fuel at the pre, mid, and post test intervals respectively, for the 25%, 50%, 75%, and 100% pedal positions. Exhaust emission data was taken at each one of the speed/load points on the maps.

Figure 9, Figure 11, and Figure 13 show the engine torque output performance maps generated with the JP-8/HRJ fuel at the pre, mid, and post test intervals respectively, for the 25%, 50%, 75%, and 100% pedal positions.

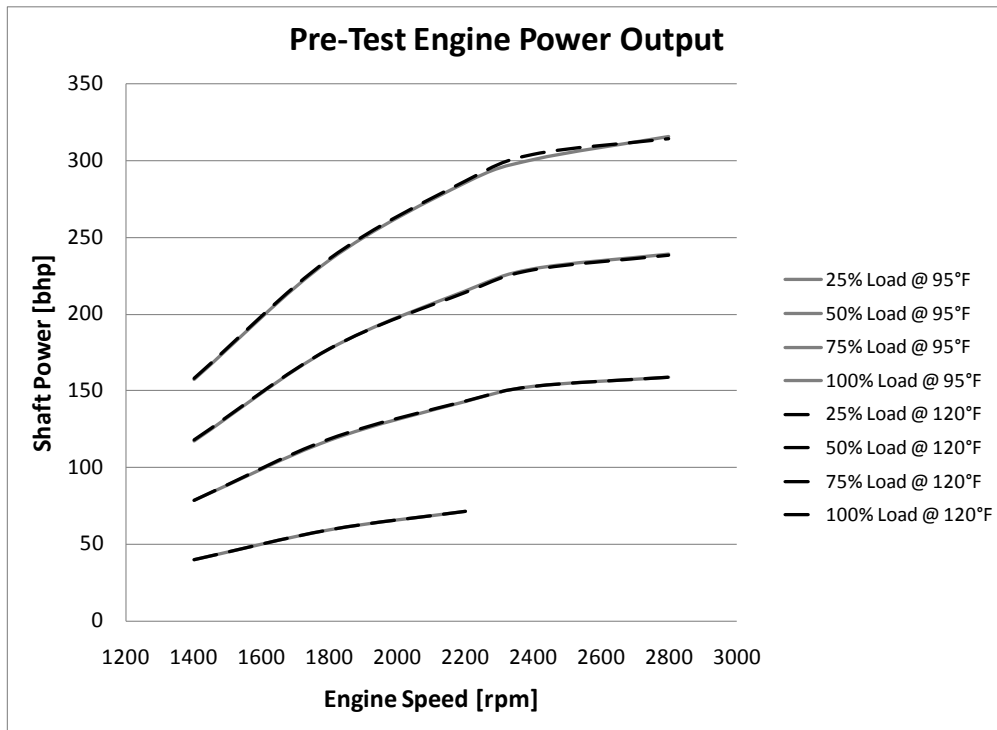


Figure 8. Pre-Test Engine Power Output

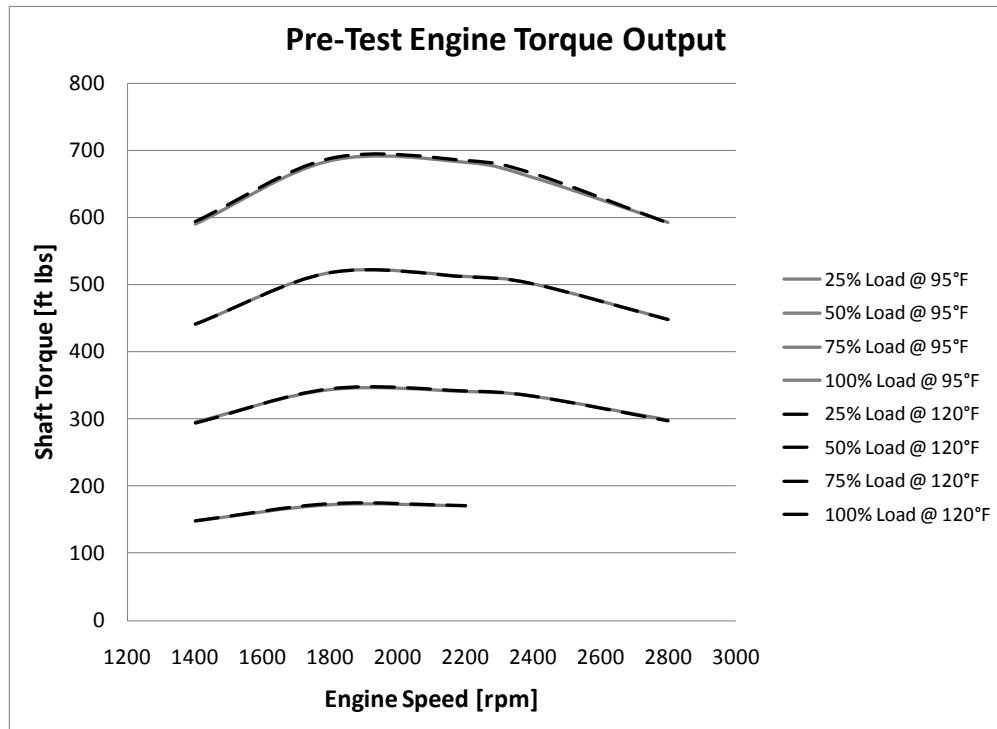


Figure 9. Pre-Test Engine Torque Output

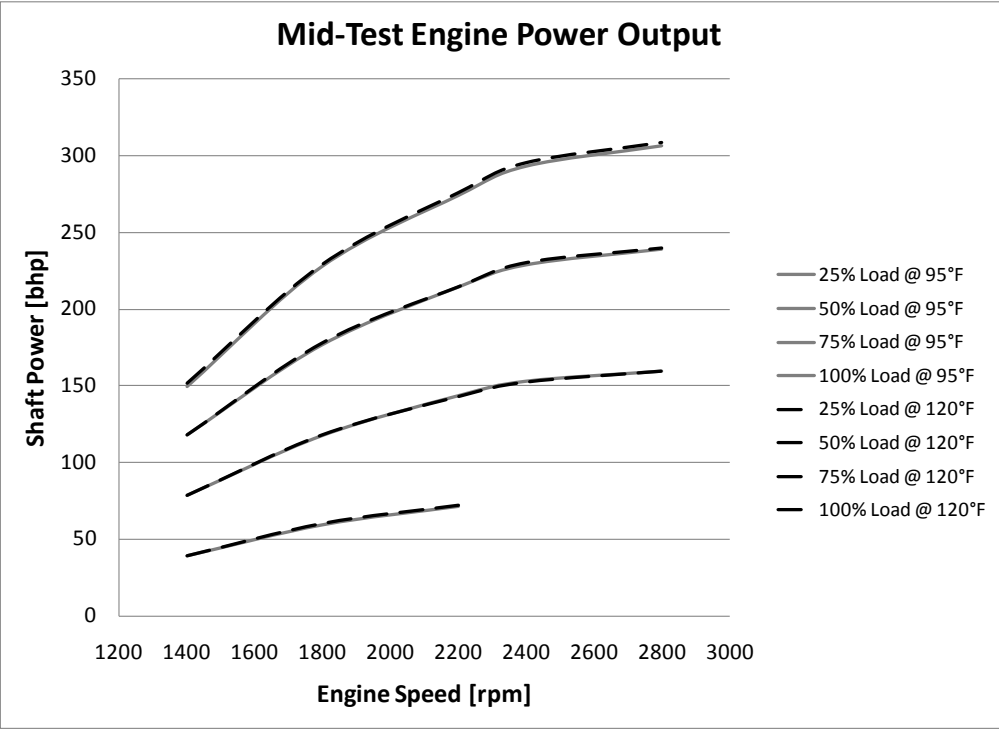


Figure 10. Mid-Test Engine Power Output

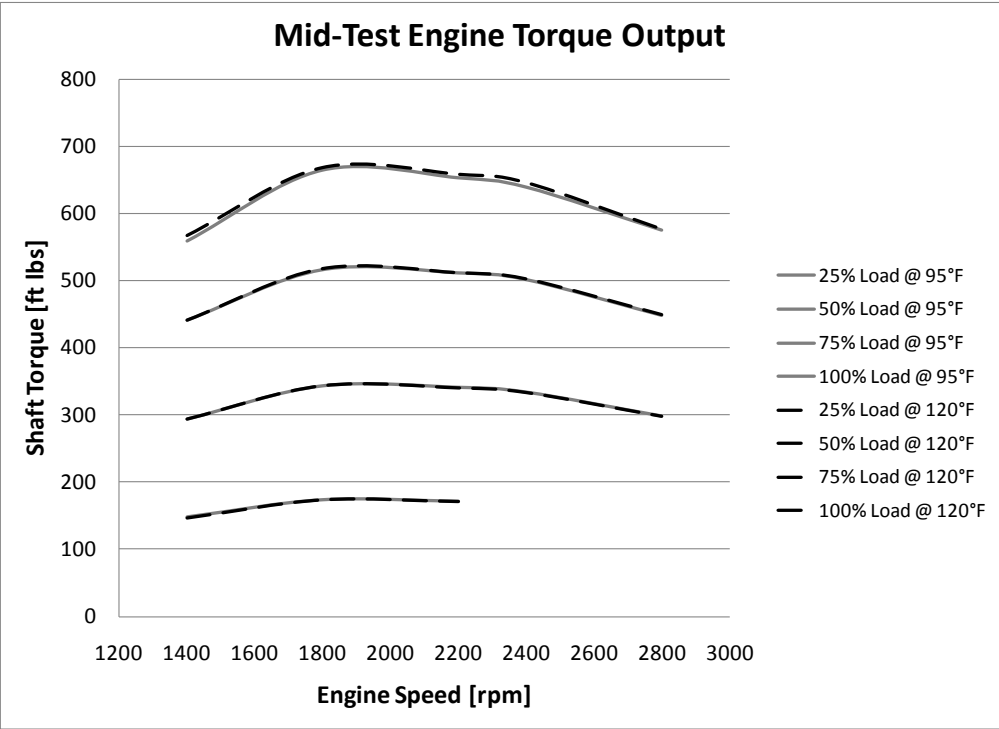


Figure 11. Mid-Test Engine Torque Output

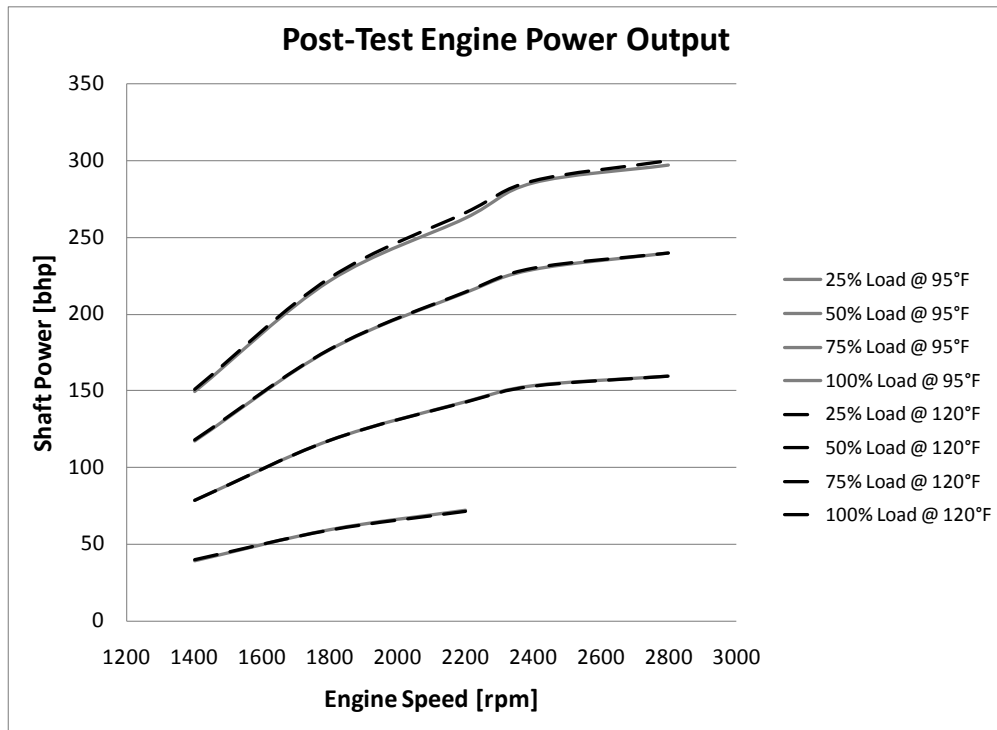


Figure 12. Pre-Test Engine Power Output

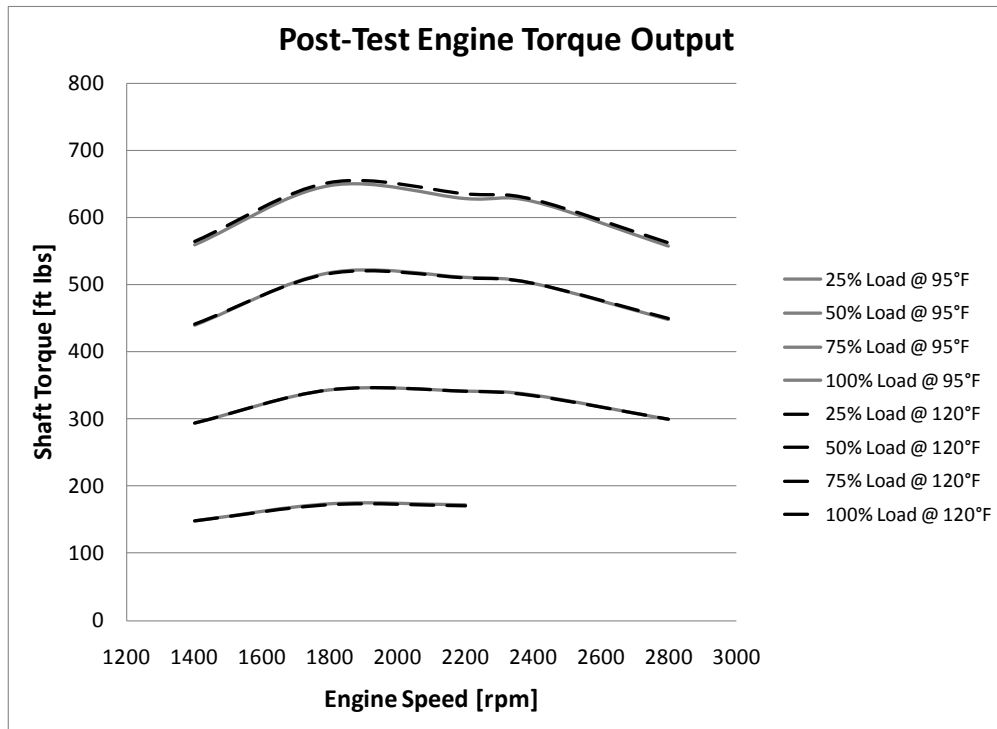


Figure 13. Post-Test Engine Torque Output

4.1.3 Engine Out Emissions

The engine out exhaust emissions for the Ford 6.7L Power Stroke diesel engine was measured as raw emissions downstream of the turbocharger outlet. The emissions instrumentation was a Horiba MEXA-1600D Motor Exhaust Gas Analyzer measurement system calibrated for detecting unburned hydrocarbon (HC), carbon monoxide (CO), carbon dioxide, oxygen, and oxides of nitrogen (NO_x) species in the exhaust. Direct engine out exhaust emission measurements were taken during the pre, mid, and post test power curve testing segments to document the engines overall condition. In addition, tailpipe emission changes over the test duration could help identify fuel system degradation and engine performance changes. Mass based calculations were determined following methodology outlined in the Code of Federal Regulations, Title 40, Part 86, and Subpart D (2). Final mass based emissions values were then correlated to engine fuel consumption rates to provide direct comparison of mass emission produced per unit mass of fuel. These values are denoted as the Emissions Index (EI).

Data shown with the 50/50% JP-8/HRJ blend are the emission measurements made prior-to, the middle, and after the 420-hour durability test. As there was little deviation between pre-test, mid-test, and post-test emission measurements, it is implicit that both the engine and fuel system integrity did not vary significantly due to the durability cycle. Figure 14, Figure 15, and Figure 16 show the HC Emissions Index (HCEI), grams HC/lb fuel, for the blend over the performance matrices performed at the two fuel temperatures, at each testing interval. As seen previously with other fuels (3), the 25% load points on the JP-8/HRJ blend show slightly higher HC, at the lean Air/Fuel Ratio (AFR) due to lower in-cylinder temperatures. The HCEI at 50% load was slightly elevated over the higher loads but less than the 25% load points. The 75% and 100% load points show similar HCEI response at the four lowest engine speeds. At the highest engine speed and richest AFR (100% load) the HCEI increases dramatically for the pre-test measurement. Subsequent measurements indicate improved HCEI at high-speeds, high loads, suggesting further engine break-in was occurring. Generally at all engine loads the HCEI shows a trend of increases with increasing engine speed, due to shorter time available for the combustion to complete.

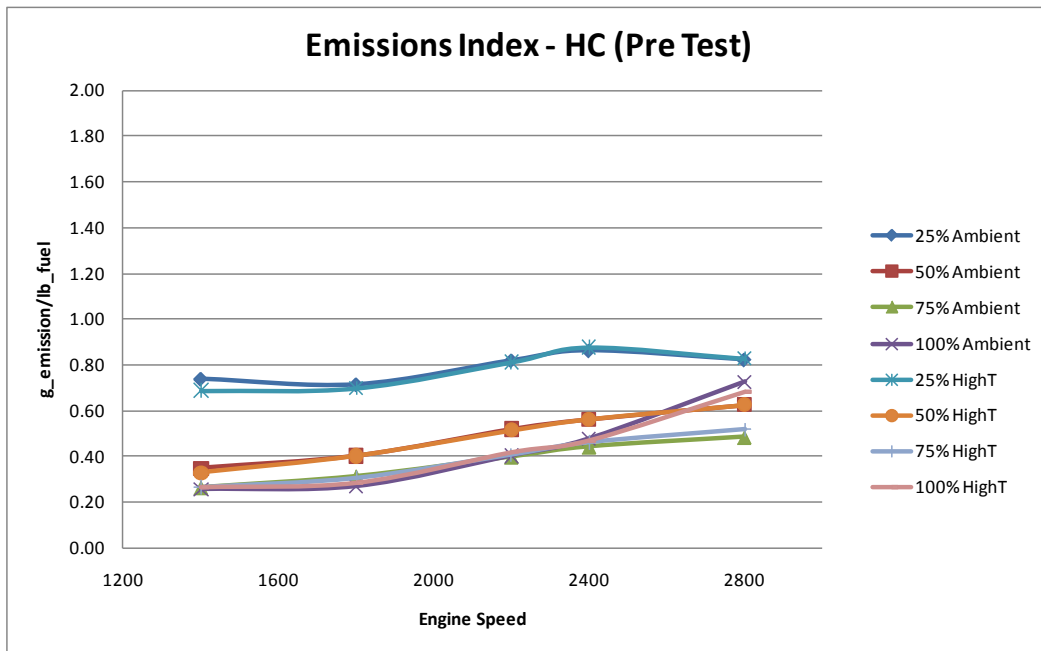


Figure 14. AF7938 50/50 JP-8/HRJ, Pre Test HC Emission

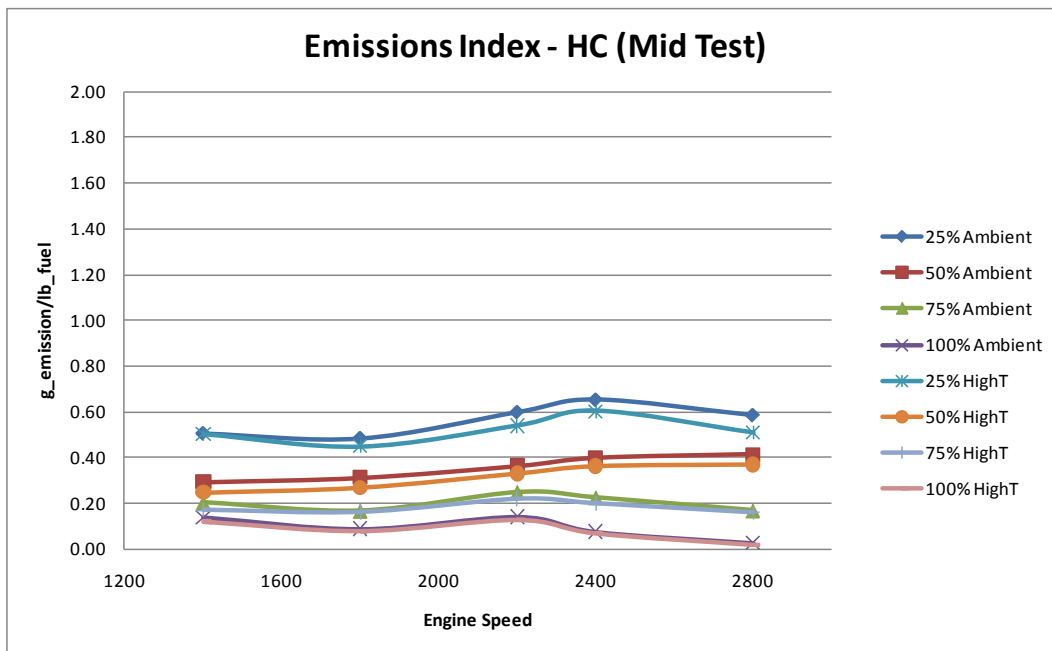


Figure 15. AF7938 50/50 JP-8/HRJ, Mid Test HC Emissions

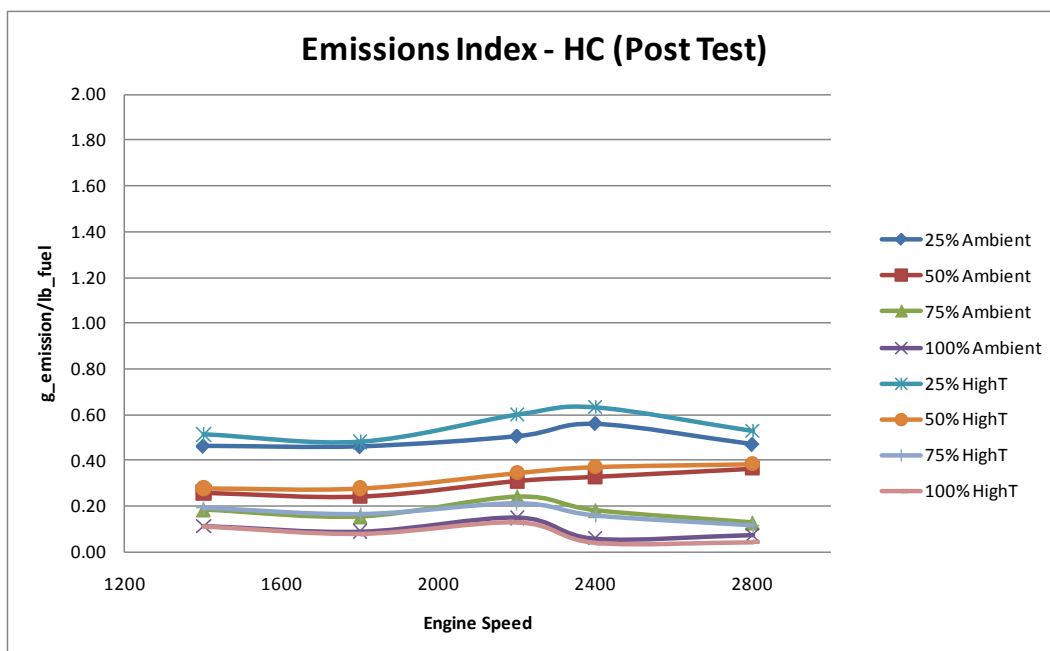


Figure 16. AF7938 50/50 JP-8/HRJ, Post Test HC Emissions

Figure 17, Figure 18, and Figure 19 show the CO Emissions Index (COEI), grams CO/lb fuel, for the JP-8/HRJ blend over the performance matrices performed at two fuel temperatures, at each testing interval. The 25% load points reveal significantly higher CO due to lower in-cylinder temperatures, and incomplete combustion at lean Air/Fuel Ratios. There is a small break-in effect for the COEI seen in the mid-test and post-test plots at the higher speed, 25% load points. The 50%, 75%, and 100% load points show similar COEI results at the two lowest engine speeds, but at higher engine speeds the 50% load points exhibit more incomplete combustion. The 75% and 100% load points have very similar COEI response with the JP-8/HRJ blend. At all engine loads the COEI increases with increasing engine speed, due to shorter time available for combustion completion.

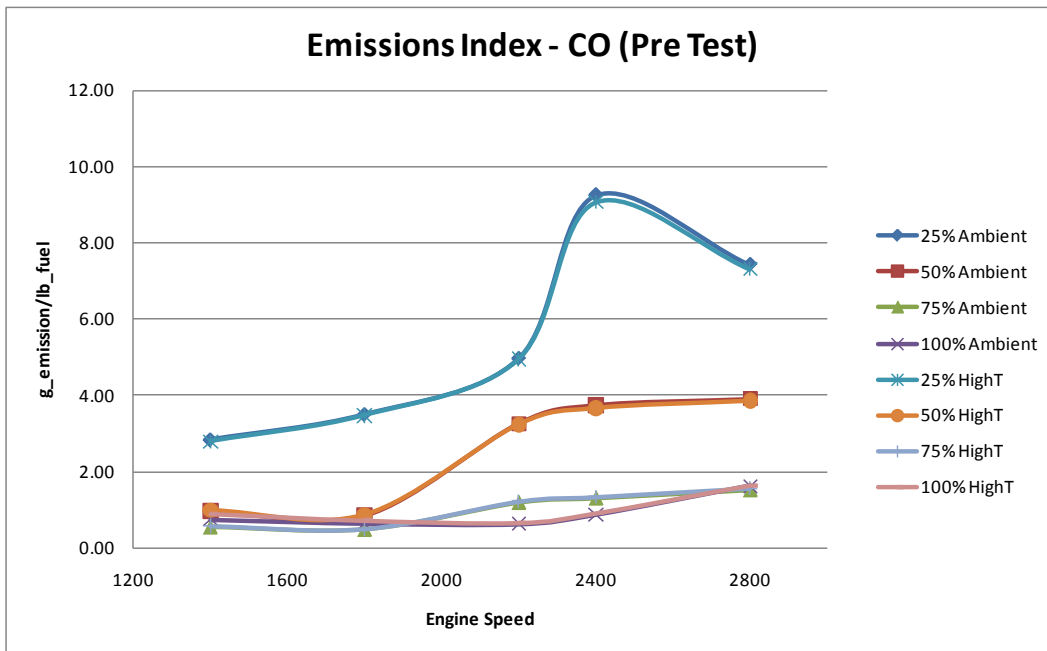


Figure 17. AF7938 50/50 JP-8/HRJ, Pre Test CO Emissions

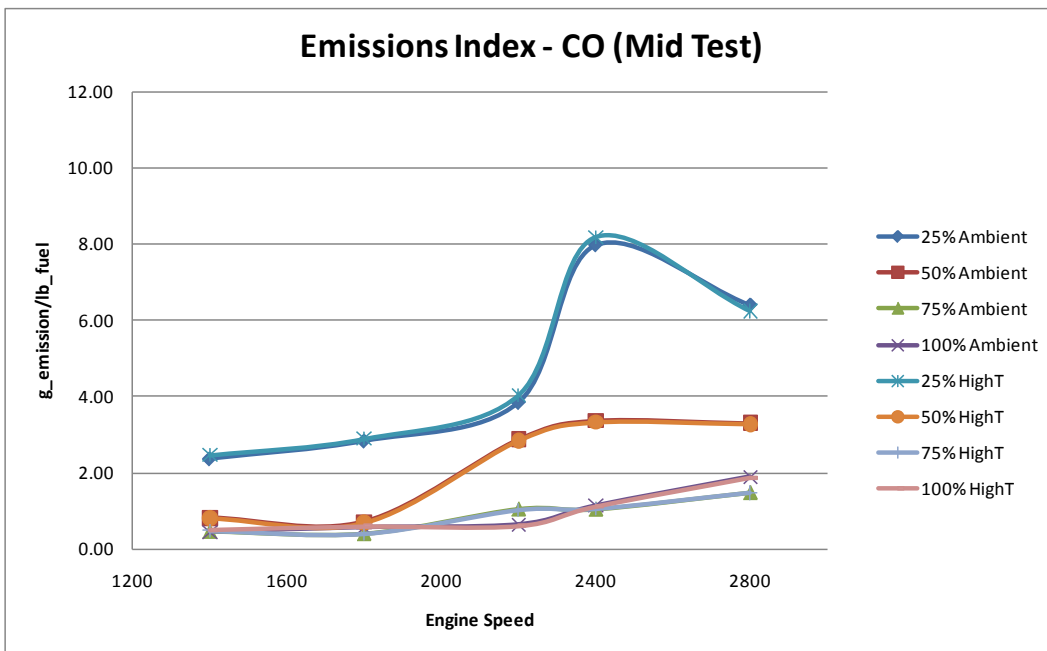


Figure 18. AF7938 50/50 JP-8/HRJ, Mid Test CO Emissions

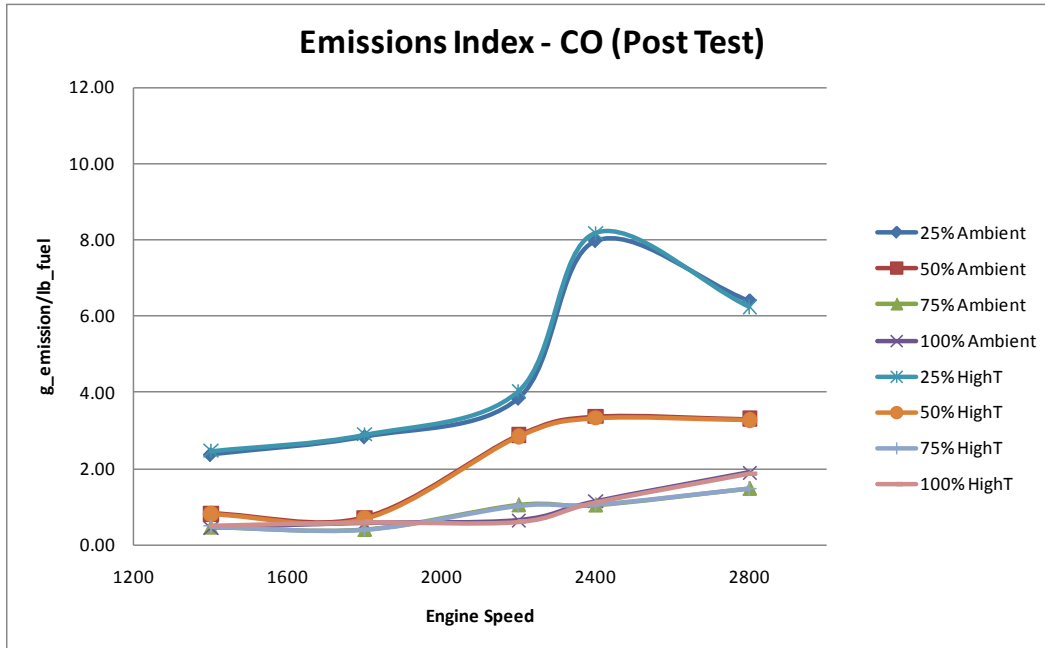


Figure 19. AF7938 50/50 JP-8/HRJ, Post Test CO Emissions

Figure 20, Figure 21, and Figure 22 shows the NOx Emissions Index (NOxEI), grams NOx/lb fuel, for JP-8/HRJ blend over the performance matrices performed at two fuel temperatures, at each testing interval. The 25% and 50% load points show the highest NOxEI, suggesting a greater portion of premixed burning during the heat release event. As the engine load increases the pilot fuel injection parameters are relatively more effective in rate-shaping the combustion event and the relative amount of NOx formed decreases. The decrease of NOxEI with increasing engine speed may be attributed to less premixed fuel from less physical time available for evaporation and mixing during the ignition delay period. The JP-8/HRJ blends NOxEI responses were very consistent throughout the testing.

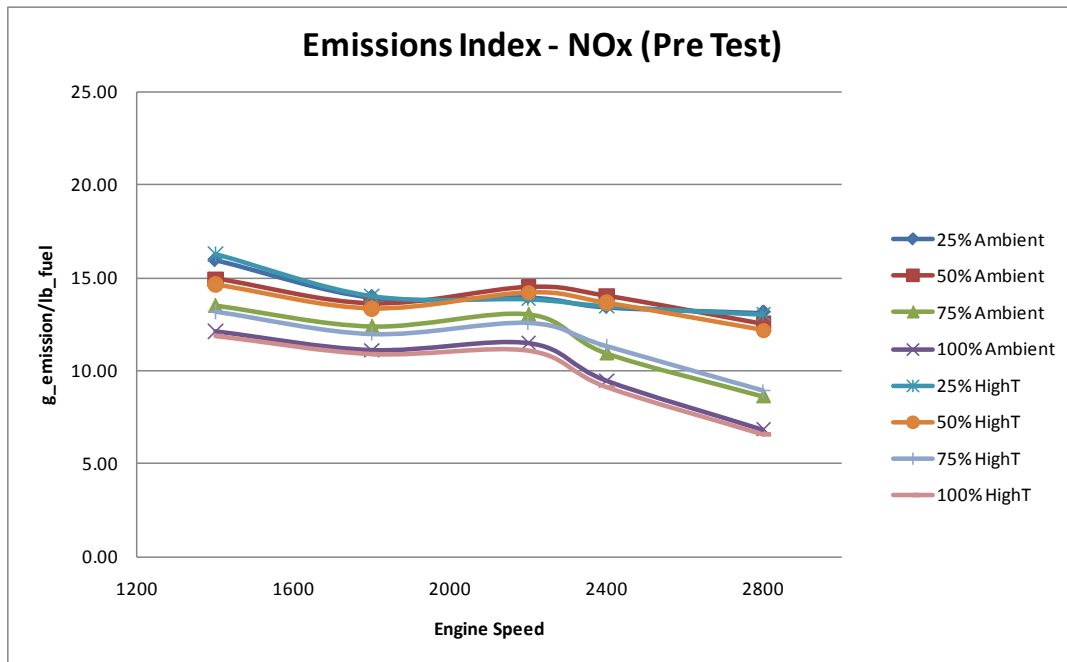


Figure 20. AF7938 50/50 JP-8/HRJ, Pre Test NOx Emissions

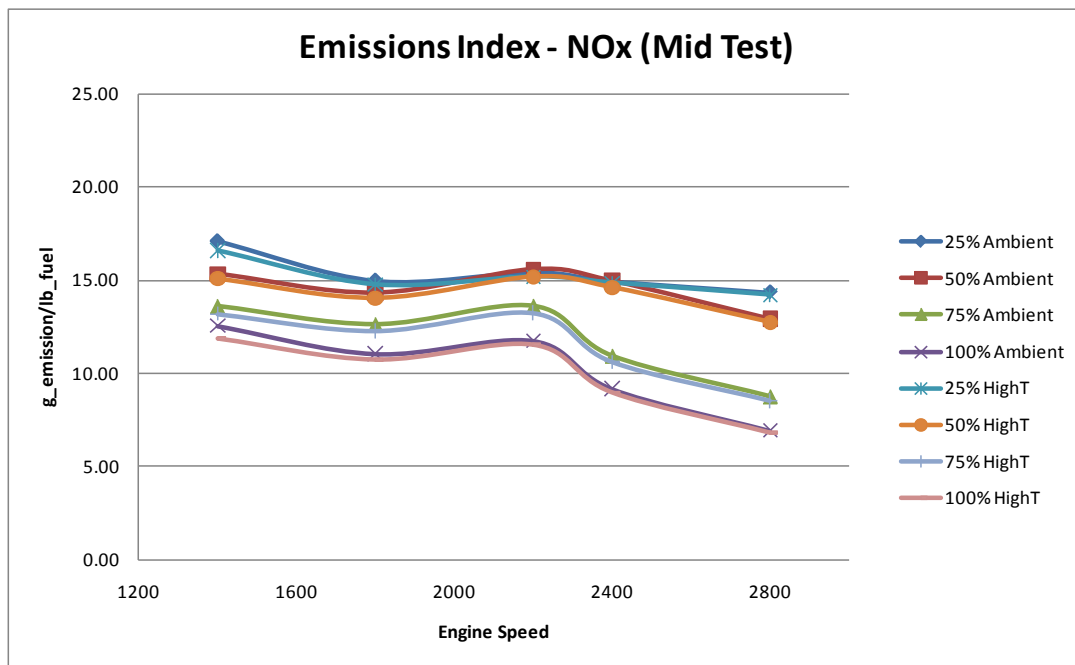


Figure 21. AF7938 50/50 JP-8/HRJ, Mid Test NOx Emissions

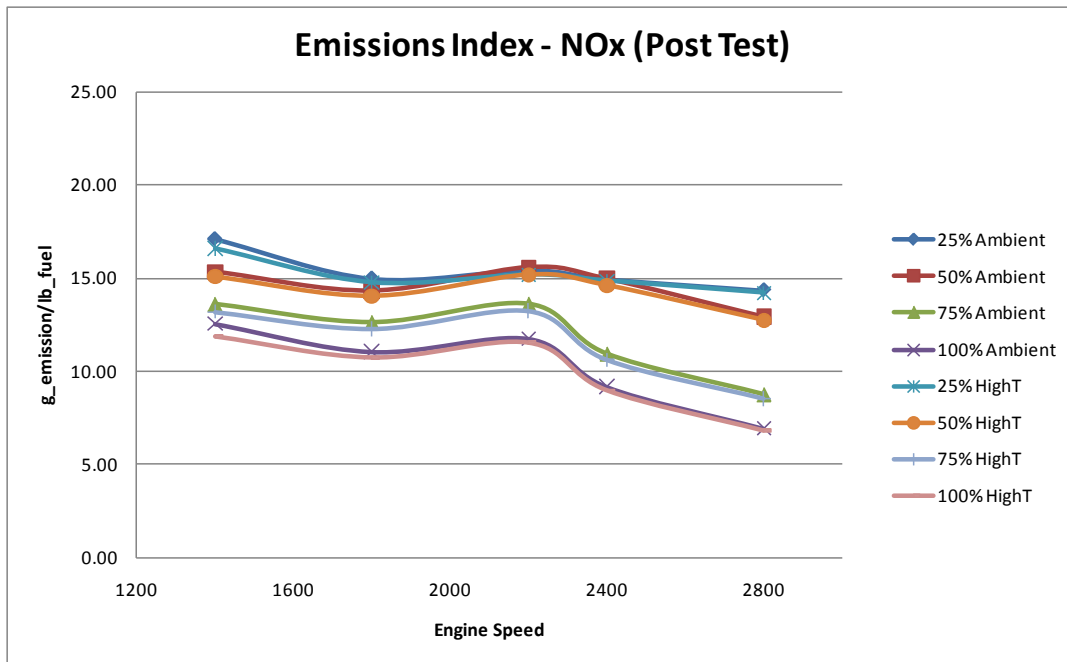


Figure 22. AF7938 50/50 JP-8/HRJ, Post Test NOx Emissions

4.1.4 Fuels Emissions Comparisons

The emission index results were lump averaged for all the data sets, at the two fuel temperatures, for each of the test fuels run to date in the 6.7L engine on both Army and Air Force programs. The results for each test fuel were normalized by the DF-2 fuel, and are shown as deviations in Figure 23. The Hydrocarbon (HCEI) and Carbon Monoxide (COEI) emissions generally represent a measure of inefficiency. The impact of the turbocharger seal oil leakage during the SPK test is apparent from the overall averaged results. The JP-8/SPK blend data suggest that the SPK fuel should result in lower HC had the turbocharger seal not leaked. The JP-8/HRJ blend revealed lower HC emissions than both JP-8 and ULSD. The COEI data suggest that synthetic fuels, either neat or as blends, effectively lowers CO emissions below both ULSD and JP-8 levels.

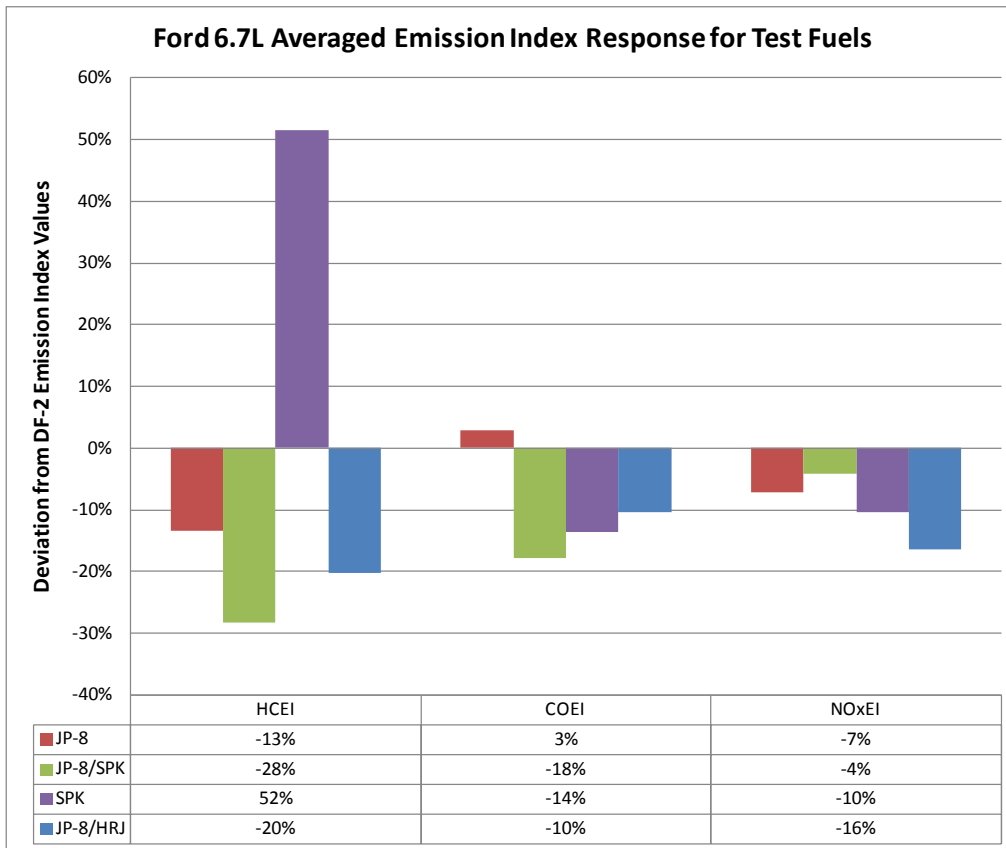


Figure 23. Fuel Specific Averaged Emission Indices

The oxides of nitrogen or NO_x emissions in a diesel engine are a measure of premixed combustion, which can be affected by fuel cetane number, and by fuel injection strategies such as pilot-injection. With increased premixed burn fraction, the temperatures in cylinder will start at a higher temperature during the diffusion-burning phase of combustion. About 80% of the fuel energy is released during diffusion burning. Thus, if the temperature at the start of diffusion burn is higher, the maximum temperature will also increase. NO_x formation is considered proportional to the time at temperatures above the NO_x formation threshold. The average NO_x emissions indices for the test fuels are also shown in Figure 23. With respect to DF-2, the JP-8, JP-8/SPK, SPK, and JP-8/HRJ test fuels revealed a reduced NOxEI when averaged over all the test points. The SPK and JP-8/HRJ blend revealed lower NOxEI levels than the neat JP-8 fuel in the 6.7L engine.

To understand the impact of fuel property variations on the Ford 6.7L engine emissions, correlation coefficients were determined for several averaged emission data sets and are shown in Table 9 for all the fuels run to date. These averaged emission data sets were the overall average (HCEI, COEI, NOxEI), the 100% load emission data (100HCEI, 100COEI, 100NOxEI), the 50% load emission data (50HCEI, 50COEI, 50NOxEI), and the 25% load emission data (25HCEI, 25COEI, 25NOxEI). Due to the turbocharger oil leak with the SPK fuel, correlation coefficients were evaluated with the HCEI values for the SPK fuel removed from the data set. The bold and highlighted values in Table 9 represent +/-0.85 or greater correlation coefficients.

The cross-correlation coefficients for the fuel property variables for the test fuels are shown in Table 10, with highlighted values representing ± 0.95 or greater correlation coefficients.

In Table 9 it can be seen that fuel density directly impacts the HCEI at the averaged and 100% conditions. An effect common for the fuel properties in Table 9 is the high load conditions (100% and 75%) often show emission response coefficients inversely proportional to the light load conditions (50% and 25%). Fuel density shows an inverse relationship with COEI at 100% load, and a direct less significant relationship with NO_xEI at all loads. The kinetic viscosity at 40°C effects the averaged and 75% load HCEI proportionately and the 100% COEI inversely.

Fuel ignition quality is determined by the fuel property variables Cetane Number (CN) and Ignition Quality Test (IQT). The cetane number compares the ignition of a test fuel when bracketed by reference fuel blends in a special test engine that operates at fixed speed and injection timing, with the compression ratio altered for ignition at Top Dead Center. The IQT correlates the measured ignition delay characteristics of a fuel with the cetane number as defined by the primary reference fuels blends in a combustion bomb. It is noted CN and IQT are highly correlated, as they are both defined by reference fuel blends. A higher CN and IQT indicate a fuel that is more reactive, and will more readily ignite at compression ignition engine cylinder conditions of temperature and pressure at fuel injection. The COEI at 25% load decreases with increasing Cetane Number. The multiple fuel injection event strategies used by the 6.7L engine may mask some of the expected ignition quality effects on emissions.

Several different fuel variables are a measure of fuel structure, those being the hydrogen/carbon atom ratio (H/C), the aromatics content (mass and volume), olefins content, and saturates content. Table 10 suggests that H/C and saturates are highly correlated with each other, and inversely proportional to the aromatics and olefins content. Data from Table 9 suggest the emissions responses follow this relationship also. The averaged HCEI shows an inverse relationship with H/C and saturate increase. The 100% load point reveals good correlations with the structure variables for emission species, as the HCEI decreases and COEI increases with H/C and saturates increase. At 75 % load the HCEI and NO_xEI also decrease with an H/C and saturate increase. At 50% and 25% load the HCEI emission response is inverse of the high load conditions response with respect to fuel structure. Of interest is the apparent correlation between emissions and the measures of fuel lubricity; however fuel lubricity has been shown to correlate with fuel structure, as seen in Table 10. Thus it is the relationship that exists between lubricity and structure that manifests the lubricity correlation with emissions. The heat of combustion (HofC) is correlated with fuel structure (H/C ratio and hydrocarbon type) and inversely with density; this is reflected in the emission index response correlation for HofC is very similar to the H/C response for emission index.

The fuel Bulk Modulus is a measure of fuel compressibility, and effects fuel injection dynamics. As the saturate content of a fuel increases, there are more highly branched molecule chains, the fuel is more compressible, and the bulk modulus would be lower. The emission index response for fuel Bulk Modulus is inversely proportional to the response seen with H/C ratio and saturates. The averaged, 100%, and 75% load HCEI had a proportional response to fuel Bulk Modulus. With feedback control for rail pressure, it is likely the apparent Bulk Modulus effect on emission index is due to the correlation with other fuel variables, specifically fuel structure. However the fuel injectors use the fuel's incompressibility as a hydraulic link to amplify the movement of the piezoelectric-stack actuator; it is feasible changes in Bulk Modulus could have had an impact on fuel injection and subsequently emissions.

The test fuels boiling point data are a measure of fuel volatility; higher boiling point temperatures indicate a less volatile fuel. The HCEI data for the engine average, 100% and 75% load points indicate HCEI emission increase as the fuels become less volatile. The COEI results at full-rack (100% loads) indicate a decrease in COEI with lower volatility fuels. The NOxEI at most conditions was not affected by the volatility of the test fuels in this data set.

Except where noted due to turbocharger oil leakage, the SPK, JP-8/ SPK, and JP-8/HRJ blends result in emissions similar to JP-8 and slightly lower than DF-2 overall. The synthetic fuels do not appear to significantly alter the gaseous emission performance of the Ford 6.7L engine.

Table 9. Correlation Coefficients of Fuel Properties with Respect to Emission Indices

Fuel Property Correlation Coefficients with Engine Emission Index With SPK HCEI Data Removed due to Turbocharger Oil leakage (r>0.85 highlighted)																			
	Density	K.Vis, 40C	H/C	CN	DCN	HofC	Aromatics, Mass	Aromatics, Volume	Olefins, Volume	Saturates, Volume	HFRR	BOCLE	Bulk Modulus	IBP	10% BP	20% BP	50% BP	90% BP	End Pt
HCEI w/o SPK	0.9752	0.8886	-0.9731	-0.5199	-0.6681	-0.9791	0.9608	0.9550	0.9074	-0.9525	-0.8916	-0.8537	0.9639	0.8384	0.9282	0.9204	0.9010	0.8876	0.8898
COEI	0.7494	0.5410	-0.7685	-0.7072	-0.7905	-0.7657	0.7823	0.7609	0.6152	-0.7480	-0.5928	-0.5412	0.7133	0.4148	0.6231	0.6061	0.5717	0.5639	0.5667
NOxEI	0.6303	0.6128	-0.6094	-0.0823	-0.5332	-0.5972	0.6465	0.6956	0.7269	-0.7025	-0.6652	-0.3870	0.6334	0.3397	0.6162	0.6029	0.5579	0.4953	0.5407
100HCEI w/o SPK	0.9498	0.8078	-0.9786	-0.3483	-0.8324	-0.9713	0.9878	0.9786	0.9023	-0.9726	-0.8748	-0.6520	0.9182	0.6421	0.8519	0.8353	0.7891	0.7415	0.7693
100COEI	-0.9783	-0.9662	0.9333	0.5308	0.6925	0.9357	-0.9428	-0.9776	-0.9907	0.9838	0.9691	0.9194	-0.9945	-0.8177	-0.9882	-0.9834	-0.9702	-0.9574	-0.9681
100NOxEI	0.6779	0.6140	-0.6706	-0.1845	-0.6242	-0.6578	0.7056	0.7419	0.7402	-0.7453	-0.6957	-0.4051	0.6698	0.3195	0.6305	0.6150	0.5672	0.5096	0.5571
75HCEI w/o SPK	0.8376	0.8732	-0.7852	-0.4502	-0.2896	-0.8052	0.7527	0.7685	0.8002	-0.7755	-0.8073	-0.9587	0.8632	0.9470	0.8859	0.8916	0.9085	0.9322	0.9112
75COEI	-0.1801	0.0444	0.2805	0.5895	0.3669	0.2846	-0.2255	-0.1228	0.0228	0.1068	0.2610	0.1839	-0.1179	0.2156	0.0081	0.0066	-0.0208	-0.1057	-0.1353
75NOxEI	0.7284	0.6802	-0.7126	-0.2092	-0.6330	-0.7015	0.7464	0.7870	0.7953	-0.7918	-0.7472	-0.4796	0.7259	0.3990	0.6949	0.6806	0.6360	0.5806	0.6246
50HCEI w/o SPK	-0.5600	-0.3504	0.6385	0.0753	0.8426	0.6128	-0.6768	-0.6535	-0.5320	0.6405	0.4909	0.0769	-0.4994	-0.0740	-0.3962	-0.3702	-0.2968	-0.2153	-0.2689
50COEI	0.6739	0.7498	-0.5907	-0.1933	-0.3842	-0.5914	0.6268	0.6986	0.7533	-0.7082	-0.5768	-0.6206	0.7129	0.7585	0.7634	0.7573	0.7311	0.6809	0.6643
50NOxEI	0.6195	0.6080	-0.5959	-0.0619	-0.5197	-0.5835	0.6349	0.6869	0.7219	-0.6942	-0.6506	-0.3747	0.6242	0.3409	0.6106	0.5971	0.5510	0.4856	0.5300
25HCEI w/o SPK	-0.7742	-0.6658	0.8035	-0.0404	0.7276	0.7872	-0.8297	-0.8387	-0.7980	0.8367	0.7742	0.4191	-0.7464	-0.4231	-0.6884	-0.6704	-0.6151	-0.5451	-0.5944
25COEI	0.7855	0.5084	-0.8344	-0.8550	-0.8961	-0.8316	0.8358	0.7864	0.5962	-0.7685	-0.6452	-0.5594	0.7302	0.3284	0.6023	0.5846	0.5542	0.5657	0.5780
25NOxEI	0.4583	0.5118	-0.4229	0.1366	-0.3282	-0.4107	0.4624	0.5275	0.6092	-0.5394	-0.5273	-0.2591	0.4761	0.2743	0.4918	0.4822	0.4420	0.3722	0.4160

Table 10. Fuel Property Cross-Correlation Matrix for All Test Fuels

Fuel Property Cross-Correlation Matrix (r>0.95 highlighted)																			
	Density	K.Vis, 40C	H/C	CN	DCN	HofC	Aromatics, Mass	Aromatics, Volume	Olefins, Volume	Saturates, Volume	HFRR	BOCLE	Bulk Modulus	IBP	10% BP	20% BP	50% BP	90% BP	End Pt
Density	1.0000																		
K.Vis, 40C	0.9015	1.0000																	
H/C	-0.9870	-0.8219	1.0000																
CN	-0.6870	-0.3541	0.7765	1.0000															
DCN	-0.8147	-0.4879	0.8927	0.8665	1.0000														
HofC	-0.9884	-0.8280	0.9997	0.7782	0.8853	1.0000													
Aromatics, Mass	0.9889	0.8308	-0.9978	-0.7456	-0.8908	-0.9967	1.0000												
Aromatics, Volume	0.9945	0.8921	-0.9819	-0.6499	-0.8272	-0.9811	0.9899	1.0000											
Olefins, Volume	0.9474	0.9799	-0.8889	-0.4204	-0.6206	-0.8909	0.9028	0.9526	1.0000										
Saturates, Volume	-0.9939	-0.9065	0.9760	0.6268	0.8076	0.9755	-0.9847	-0.9994	-0.9626	1.0000									
HFRR	-0.9774	-0.9273	0.9542	0.6075	0.7341	0.9570	-0.9521	-0.9666	-0.9577	0.9702	1.0000								
BOCLE	-0.8961	-0.9461	0.8380	0.5383	0.5150	0.8488	-0.8264	-0.8559	-0.9017	0.8653	0.9212	1.0000							
Bulk Modulus	0.9931	0.9458	-0.9616	-0.6121	-0.7423	-0.9643	0.9655	0.9863	0.9743	-0.9897	-0.9815	-0.9278	1.0000						
IBP	0.7086	0.9252	-0.5913	-0.1561	-0.1803	-0.6034	0.5978	0.6818	0.8372	-0.7028	-0.7362	-0.8961	0.7830	1.0000					
10% BP	0.9434	0.9933	-0.8783	-0.4487	-0.5800	-0.8835	0.8862	0.9349	0.9886	-0.9455	-0.9516	-0.9512	0.9758	0.8931	1.0000				
20% BP	0.9356	0.9955	-0.8676	-0.4368	-0.5596	-0.8733	0.8747	0.9250	0.9852	-0.9363	-0.9477	-0.9565	0.9705	0.9038	0.9996	1.0000			
50% BP	0.9206	0.9950	-0.8493	-0.4315	-0.5237	-0.8565	0.8528	0.9032	0.9719	-0.9154	-0.9409	-0.9722	0.9591	0.9208	0.9950	0.9974	1.0000		
90% BP	0.9218	0.9798	-0.8581	-0.4911	-0.5360	-0.8667	0.8547	0.8947	0.9501	-0.9053	-0.9449	-0.9910	0.9559	0.9090	0.9832	0.9866	0.9945	1.0000	
End Pt	0.9393	0.9797	-0.8820	-0.5095	-0.5752	-0.8895	0.8793	0.9157	0.9617	-0.9254	-0.9645	-0.9847	0.9685	0.8838	0.9862	0.9882	0.9932	0.9977	1.0000

4.1.5 Engine Oil Analysis

Table 11 on the next page shows the engine used oil analysis over the test duration. No oil changes were required during each 210-hour segment of testing. Plots of various pertinent used oil property trends are shown subsequently.

4.1.6 Engine Oil Analysis Trends

Figure 24 shows the lubricant viscosity change throughout testing with the 5W-40 grade lubricant. The lubricant did thicken, increase out of grade (>16.3 cSt @ 100°C) prior to the 210-hour change, but as shown in Figure 25 there was still reserve alkalinity, or Total Base Number (TBN). Generally in engine testing the TBN should be greater than 4.0, or the TBN should be greater than the Total Acid Number (TAN). Figure 24 and Figure 25 indicate there was lubricant hang-up in the engine at the 210-hour change interval, since the viscosity, TBN, and TAN values did not drop to new oil levels after the change. Figure 24 suggests that the lubricant reached the end of its service life at the 420-hour point, as the TAN and TBN were equal, and from Figure 24 the viscosity had increased above grade.

Table 11. Engine Oil Analysis for 420-Hour 50/50 JP-8/HRJ Diesel Engine Test

Property	ASTM Test	Test Hours																				
		0	21	42	63	84	105	126	147	168	189	210	231	252	273	294	315	336	357	378	399	420
Density	D4052	0.854	0.859	0.863	0.865	0.867	0.870	0.873	0.876	0.880	0.883	0.886	0.862	0.866	0.870	0.873	0.876	0.881	0.883	0.886	0.889	0.892
Viscosity @ 100°C (cSt)	D445	14.1	14.1	14.4	14.7	15.1	15.6	16.0	16.4	17.0	17.6	18.1	14.9	15.5	16.0	16.5	17.0	17.5	18.1	18.8	19.5	20.3
Total Base Number (mg KOH/g)	D4739	8.8	7.6	6.8	6.5	6.3	5.6	5.3	5.1	5.7	5.6	4.7	8.0	7.2	6.4	6.1	5.8	6.4	5.0	4.5	4.8	4.4
Total Acid Number (mg KOH/g)	D664	1.7	2.3	2.3	2.6	2.4	2.8	3.2	3.1	3.4	3.7	3.6	2.2	2.4	2.8	3.0	3.0	2.9	3.2	3.4	4.1	4.4
Oxidation (Abs./cm)	E168 FTNG	0.0	1.3	2.8	4.2	5.6	7.1	7.7	8.6	9.5	11.5	11.7	2.0	3.3	4.8	6.0	7.0	8.4	9.3	9.7	10.5	11.3
Nitration (Abs./cm)	E168 FTNG	0.0	0.7	1.4	1.7	1.9	1.9	1.7	1.5	1.1	1.3	2.1	1.0	1.9	2.6	2.9	3.1	3.2	3.5	2.6	2.2	2.2
Soot	Soot	0.2	0.7	1.2	1.7	2.2	2.8	3.1	3.6	4.1	4.8	5.2	1.4	2.0	2.7	3.3	3.8	4.4	5.1	5.5	6.1	6.6
Wear Metals (ppm)	D5185																					
Al		1	3	4	5	6	7	7	7	8	8	8	3	3	3	3	4	4	4	5	5	5
Sb		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
B		73	46	40	31	28	27	26	26	26	25	27	43	34	32	29	26	27	26	24	24	24
Ca		840	1018	1038	1044	1084	1110	1111	1135	1163	1131	1177	889	887	937	972	954	962	1001	1020	1027	1033
Cr		<1	1	2	2	3	4	4	4	4	5	5	1	2	2	3	3	3	4	4	4	5
Cu		<1	6	8	9	10	11	12	12	13	14	14	3	3	4	4	5	5	6	6	6	7
Fe		1	19	37	56	78	108	138	169	222	268	326	57	70	102	137	175	211	261	311	349	410
Pb		<1	<1	<1	<1	<1	<1	<1	1	1	1	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Mg		1128	1066	1123	1140	1167	1210	1233	1259	1346	1297	1385	1239	1242	1310	1350	1351	1335	1368	1438	1421	1453
Mn		<1	<1	<1	1	1	2	2	2	2	2	3	<1	<1	<1	1	1	2	2	2	2	3
Mo		66	61	63	62	66	69	70	72	74	76	78	71	68	74	76	78	75	79	86	83	82
Ni		<1	<1	<1	<1	<1	<1	<1	<1	<1	1	1	<1	<1	<1	<1	<1	<1	<1	1	1	1
P		1104	1059	1057	1061	1055	1072	1087	1101	1127	1125	1179	1075	1063	1129	1117	1104	1117	1167	1212	1161	1185
Si		4	6	7	6	7	7	7	7	8	8	8	6	6	7	7	7	7	7	8	8	8
Ag		<1	2	3	4	5	6	7	7	8	7	6	2	2	3	3	3	3	3	3	3	3
Na		7	8	9	9	10	11	12	12	12	11	12	8	9	12	11	10	12	13	16	12	12
Sn		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Zn		1254	1279	1295	1289	1283	1326	1388	1412	1499	1525	1510	1323	1353	1403	1426	1413	1461	1525	1537	1515	1536
K		<5	<5	<5	<5	5	5	<5	<5	<5	6	7	6	<5	<5	5	<5	<5	<5	5	5	5
Sr		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
V		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ti		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cd		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

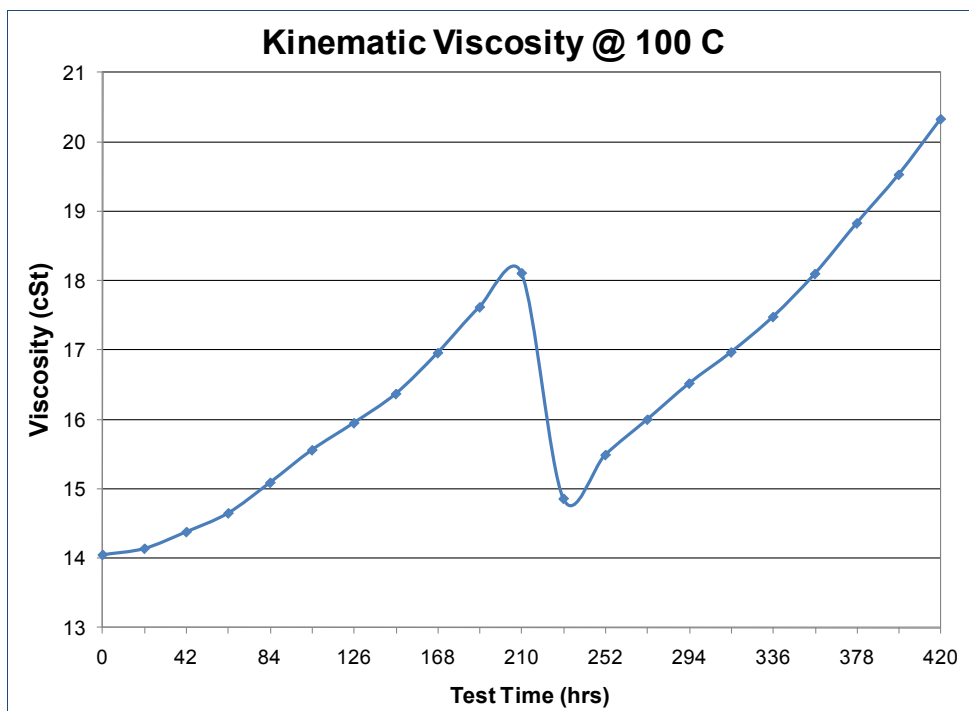


Figure 24. Lubricant Kinematic Viscosity Change

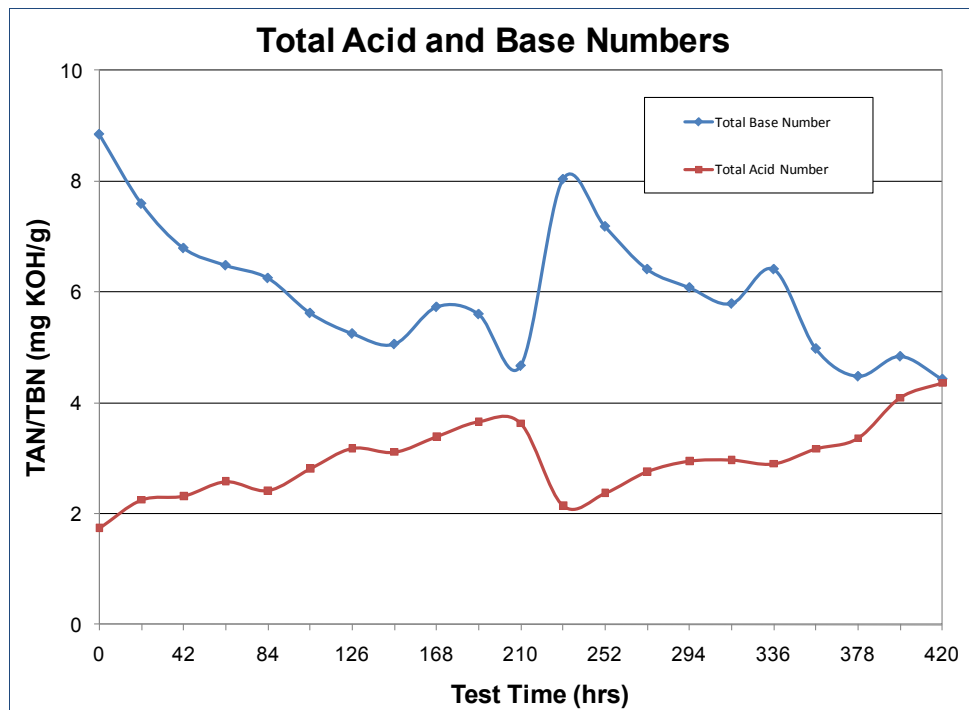


Figure 25. Lubricant Acid and Base Number Change

The soot accumulation in the lubricant is shown in Figure 26. A comparison of the soot accumulation and the viscosity change suggest soot accumulation in the lubricant was at least partially responsible, along with lubricant oxidation, for the viscosity increases that are shown in Figure 24. The kinematic viscosity change, TBN depletion and soot aggregation rates for the 50/50 HRJ/JP-8 fuel at 210-hours was very similar to the rates seen with JP-8 fuel at the same test interval seen in Reference 3.

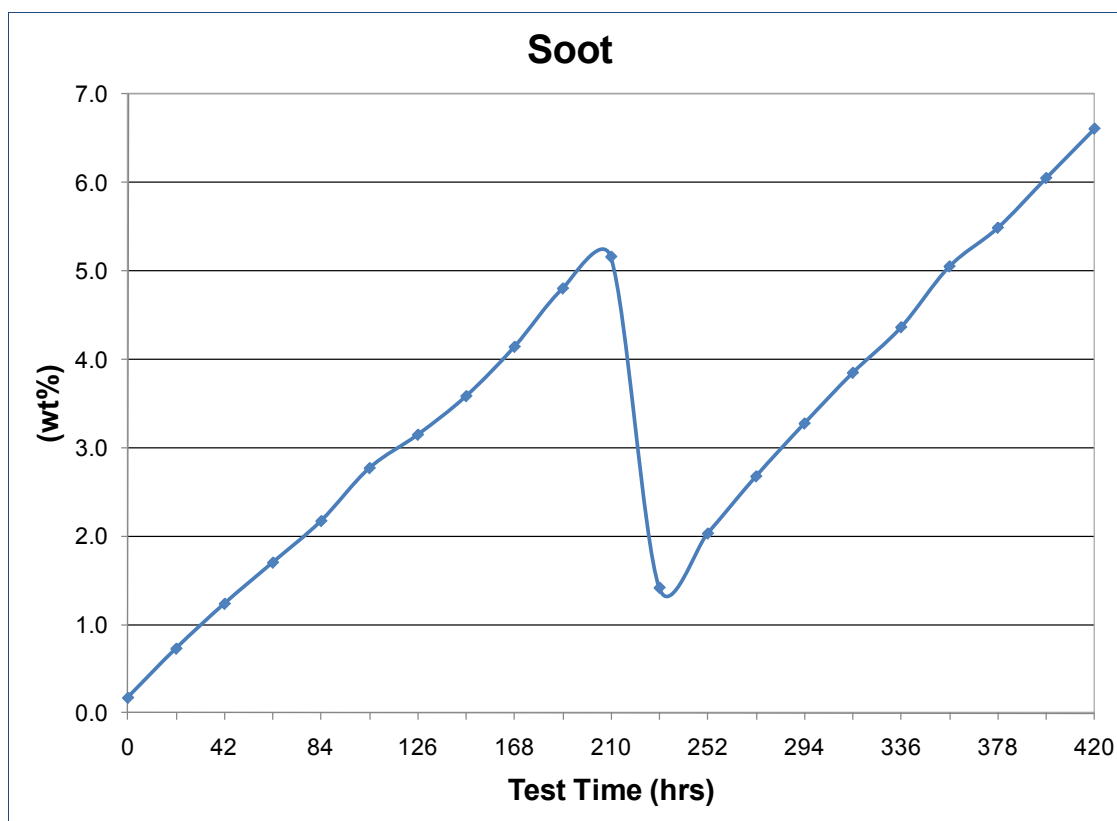


Figure 26. Lubricant Soot Accumulation

The accumulations of the common indicator wear metals in the lubricant for the engine testing are shown in Figure 27. The lead (Pb) and copper (Cu), usually indicative of bearing wear, were present at very low levels, typical of the values seen previously with the 6.7L engine. The aluminum (Al) would indicate piston wear, but was also at very low levels, considered normal for this engine. The iron (Fe) is indicative of cylinder bore wear, caused by the piston, piston ring, and cylinder liner contact. The levels of Fe seen for this test were elevated from the previous engine for the previous fuels testing done with 6.7 L engines using the wheeled vehicle cycle(3). However, the level of Fe seen for this 6.7 L engine was similar to other military use engines that had been run on the same test cycle.

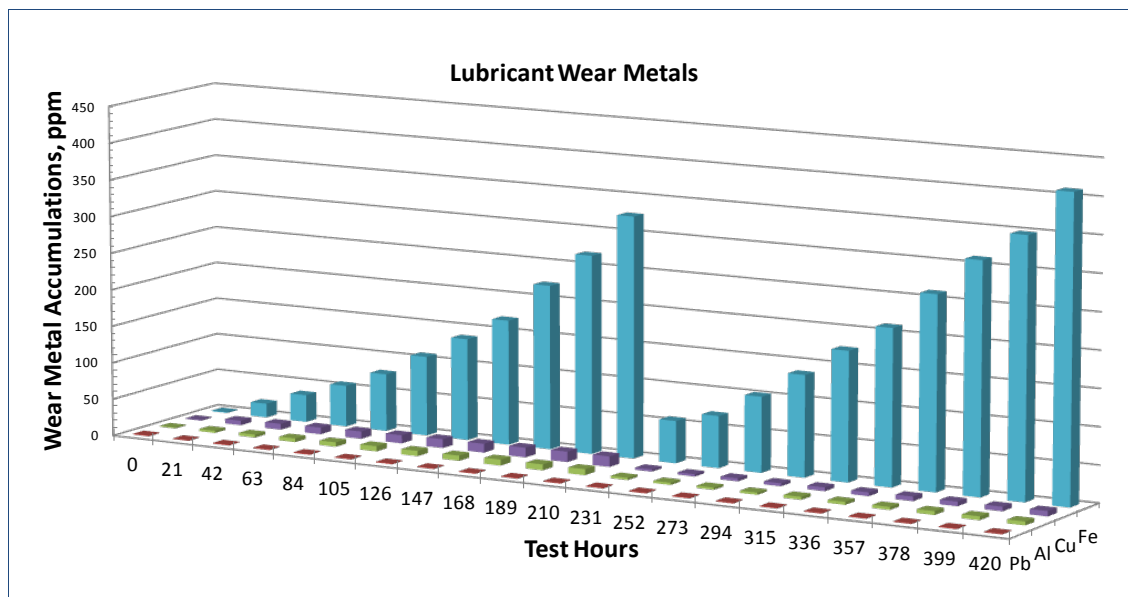


Figure 27. Test Duration Wear Metals Accumulations

4.1.7 Oil Consumption Data

A tally sheet was kept of all lubricant addition, samples, and drains from the 6.7L engine during the testing. The tally sheet is shown in Table 12. The average oil consumption per test hour for the JP-8/HRJ testing was 0.062 lbs/hour, which compares with previous experience with the 6.7L engine for the same test cycle.

Table 12. Lubricant Additions Over Test Duration

	Additions (lbs)	Samples (lbs)	Consumption (lbs)	Consumption Accumulated
21 -hr	0.89	0.24	0.65	0.65
42 -hr	1.25	0.23	1.02	1.67
63 -hr	1.30	0.24	1.06	2.73
84 -hr	1.70	0.25	1.45	4.18
105 -hr	1.75	0.24	1.51	5.69
126 -hr	1.74	0.24	1.50	7.19
147 -hr	1.45	0.24	1.21	8.40
168 -hr	1.38	0.24	1.14	9.54
189 -hr	1.67	0.25	1.42	10.96
210 -hr	1.77	0.25	1.52	12.48
231 -hr	0.90	0.24	0.66	13.14
252 -hr	1.47	0.24	1.23	14.37
273 -hr	1.74	0.24	1.50	15.87
294 -hr	1.60	0.24	1.36	17.23
315 -hr	1.78	0.24	1.54	18.77
336 -hr	1.58	0.24	1.34	20.11
357 -hr	1.73	0.25	1.48	21.59
378 -hr	1.59	0.24	1.35	22.94
399 -hr	1.70	0.25	1.45	24.39
420 -hr	1.72	0.25	1.47	25.86
	Initial Fill	23.52	Total Additions	30.71
	210 Drain	23.5	Total Samples	4.85
	210 Fill	23.87		
	EOT Drain	23.62		
	(Initial Fill + 210 Fill + Additions)		78.10	
	(210 Drain + EOT Drain + Samples)		51.97	
	Total Oil Consumption		26.13	

4.1.8 Post Test Fuel Injection Hardware Inspection

The fuel injection pump can be broken down into four critical areas for evaluation: the interface of the fuel pump body bore and cam follower, cam and roller interface, cam and bushing (bearing) interface, and high pressure plunger and barrel. A visual inspection and description of each of these components can be seen below in Table 13, followed by discussion of wear present and representative pictures. Inspections indicate the wear seen at 420-hours with the HRJ blend is very similar to the wear results seen in earlier Army/Air Force tests with all other fuels at 210-hours as shown in Table 13. The component inspections for all prior Army/Air Force fuels testing with the Ford 6.7 L engine are documented in Reference 3.

Table 13. Injection System Component Inspections

Test Hours	0	210	210	210	210	420
Part/Fuel	New	DF-2	JP-8	JP-8/SPK	SPK	JP-8/HRJ
Volume Control Valve	New	As new	As new	As new	As new	As new
Pump Body	Very light polish of bores	Very light polish of bores, top & bottom	Very light polish of bores, top & bottom	Light polish & light scuff of bores, top & bottom	Light polish & very light scuff of bores, top & bottom	Light polish & very light scuff of bores, top & bottom
Pump Bushings	Both new	Both as new	Both as new	Both as new	Both as new	Discoloration at zones corresponding to load direction, otherwise as new
Cam	Visible light grinding marks	Light polish, not measureable, seal contact wear	Light polish & very light burnish, not measureable, seal contact wear	Polish & light burnish, not measureable, seal contact wear, journals V.L. burnish	Light polish & very light burnish, not measureable, seal contact wear	Light polish & very light burnish, not measureable, seal contact wear
Roller - Left	New, bright & shiny	Light polish	Very light burnish & polish	Light burnish & polish, Heavy roller end wear against follower	Very light burnish & polish	Very light burnish & polish
Roller - Right	New, bright & shiny	Light polish	Very light burnish & polish	Light burnish & polish	Very light burnish & polish	Very light burnish & polish
Roller Shoe - L	New	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button
Roller Shoe - R	New	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button
Follower - L	New	Very light polish	Polish, very light scuff, top & bottom	Polish, light scuff, top & bottom	Polish, very light scuff, top & bottom	Polish, light scuff, top & bottom
Follower - R	New	Very light polish	Polish, very light scuff, top & bottom	Polish, light scuff, top & bottom	Polish, very light scuff, top & bottom	Polish, light scuff, top & bottom
Plunger - L	New	As new, very light polish on plunger button, more than right	As new, light polish on plunger button, more than right	As new, light polish on plunger button, more than right, more polish than JP-8	As new, light polish on plunger button, more than right	As new with one very light circumferential scratch, light polish on plunger button, more than right
Plunger - R	New	As new, very light polish on plunger button	As new, light polish on plunger button	As new, light polish on plunger button	As new, light polish on plunger button	As new, light polish on plunger button
Barrel - L	New	As new	As new	As new	As new	As new
Barrel - R	New	As new	As new	As new	As new	As new
Inlet Check - L	New	As new	As new	As new	As new	As new
Inlet Check -R	New	As new	As new	As new	As new	As new

4.1.9 Post Test Fuel Injection Hardware Photos (No Magnification)

The following photos document the post test fuel injection hardware condition. Figure 28 and Figure 29 below show a representative photo of the HPCR pump body. Frame of reference for left and right notations are taken from Figure 29 as the pump is installed in the engine.



Figure 28. HPCR Pump Body, Front (Representative Photo)



Figure 29. HPCR Pump Body, Rear (Representative Photo)

Figure 30 shows the left hand pump body bore. Figure 31 shows a close up picture of the light polish found on the bore surface from interaction with the cam follower assembly. The wear present on the pump body bore and cam follower surfaces were found to be similar to previous fuels testing. The bores in each of the pumps showed some polishing on their surface from interactions with the cam follower. Markings tended to be present primarily at the top and bottom of the travel area of the follower, which is consistent with areas of largest side loading present on the follower from the forces applied by the pumps camshaft and plunger return spring. A new unused pump also shows similar but smaller markings likely produced at end of line testing during manufacturing.



Figure 30. AF7938 50/50 JP-8/HRJ, Post Test, Left Pump Bore

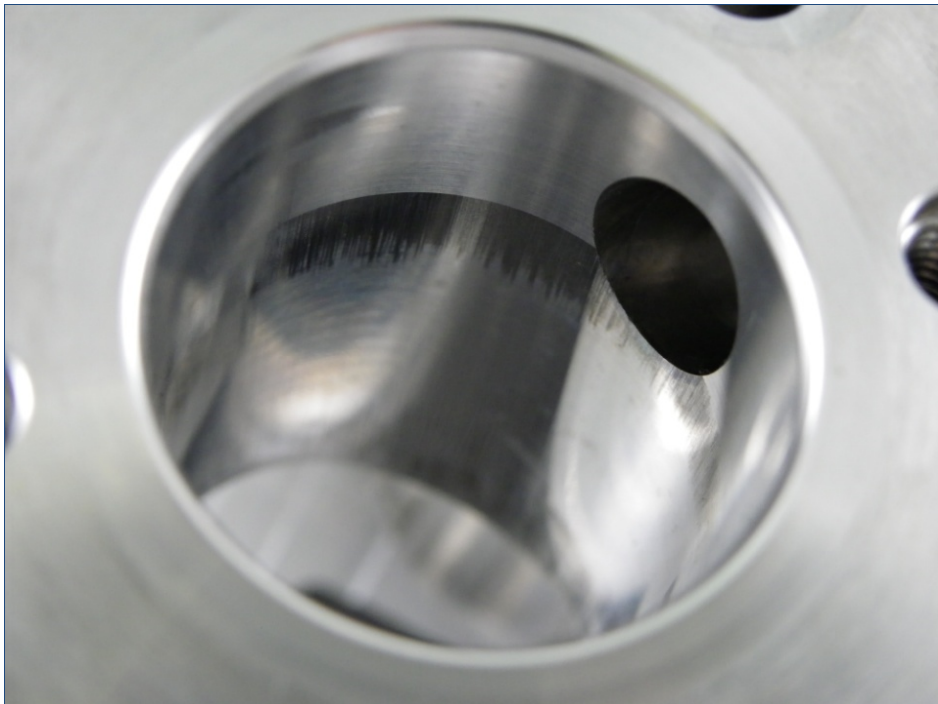


Figure 31. AF7938 50/50 JP-8/HRJ, Post Test, Left Pump Bore Close

Figure 32 shows the right hand pump body bore. Figure 33 below shows a close up picture of the light polish found on the bore surface, similar to the left hand bore. The follower bore wear for the left and right sides of the pump were very similar.

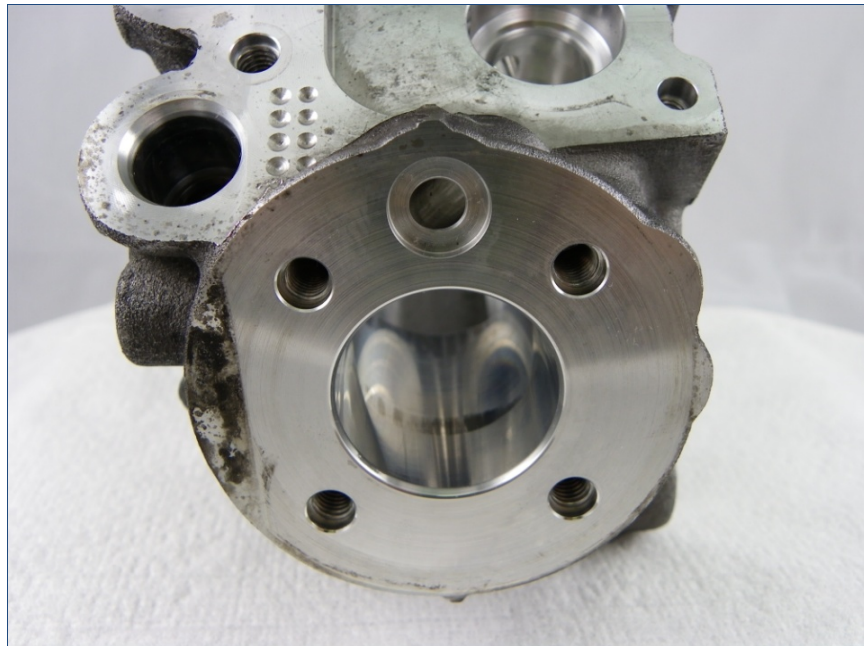


Figure 32. AF7938 50/50 JP-8/HRJ, Post Test, Right Pump Bore

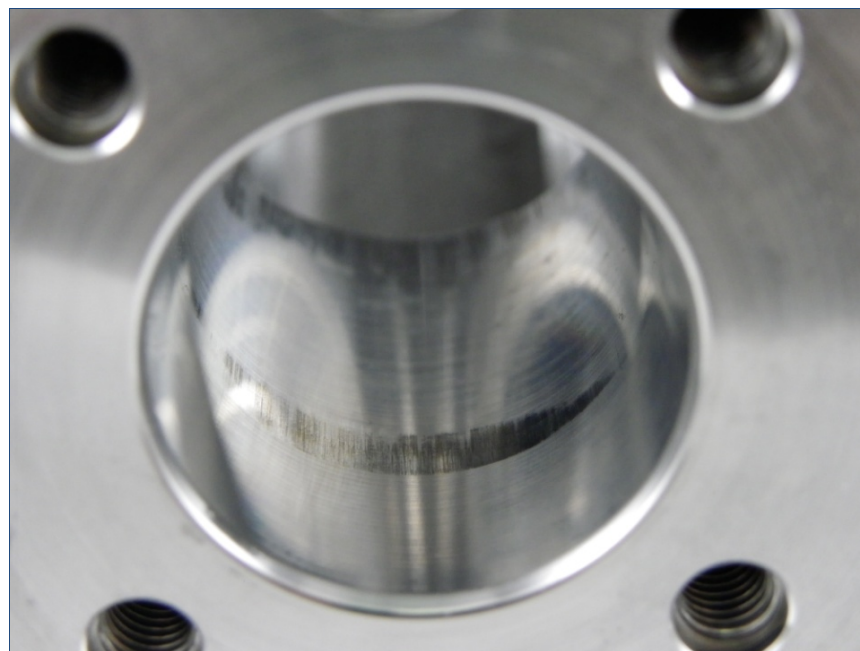


Figure 33. AF7938 50/50 JP-8/HRJ, Post Test, Right Pump Bore Close

Figure 34 shows the left bore cam follower and roller assembly. The follower was oriented to show the most severe areas of wear present on the follower surface. All follower surfaces showed polishing and light scuffing on their surfaces consistent with the polishing found on the pump bore surface. This again corresponded with areas that typically experience the greatest side load forces. Compared to the ULSD follower from previous testing that showed some minor scuffing, the JP-8/HRJ blend components contained a slightly larger scuffed area. This is attributed to the reduction in lubricity and viscosity of the military fuel when compared to the ULSD. Figure 35 shows the left hand roller surface, with light burnishing evident.



Figure 34. AF7938 50/50 JP-8/HRJ, Left Cam Follower



Figure 35. AF7938 50/50 JP-8/HRJ, Left Cam Follower Roller

Figure 36 shows the left cam follower under crown and the contact area with the high pressure plunger head. Figure 37 shows the left hand high pressure plunger. Note the similar contact markings where it contacts the follower under crown. Polishing at this interface was visible, but no physical wear was tactically distinguishable.



Figure 36. AF7938 50/50 JP-8/HRJ, Left Cam Follower Under Crown

The barrel and plunger assemblies for the test did not show any wear distinguishing themselves from the new unused components. All surfaces treating to the high pressure plunger was intact and showed no variation. The inside diameter of the barrel surfaces also appeared to be smooth and unworn.



Figure 37. AF7938 50/50 JP-8/HRJ, Left High Pressure Plunger

Figure 38 shows the right bore cam follower and roller assembly. The follower was oriented to show the most severe areas of scuffing present on the follower surface. Figure 39 shows the right hand roller surface. The follower and roller wear for the left and right sides of the pump were very similar for the JP-8/HRJ test. The overall follower and roller wear for the 420-hour JP-8/HRJ test was very similar to the other military fuels run in 210-hour tests previously.



Figure 38. AF7938 50/50 JP-8/HRJ, Right Cam Follower



Figure 39. AF7938 50/50 JP-8/HRJ, Right Cam Follower Roller

Figure 40 shows the right cam follower under crown and the contact area with the high pressure plunger head. Figure 41 shows the left hand high pressure plunger. Similar to the left hand assembly, polishing at this interface was visible, but no physical wear was tactically distinguishable. The right barrel and plunger assembly wear was similar to that seen on the left, and similar to all previously run test fuels.



Figure 40. AF7938 50/50 JP-8/HRJ, Right Cam Follower Under Crown



Figure 41. AF7938 50/50 JP-8/HRJ, Right High Pressure Plunger

Figure 42 and Figure 43 below show the pump body rear and front camshaft bushings respectively. The bushings showed no signs of wear with the JP-8/HRJ fuel at 420-hours, or with any of the other fuels tested in the 6.7L engine using the wheeled vehicle cycle.

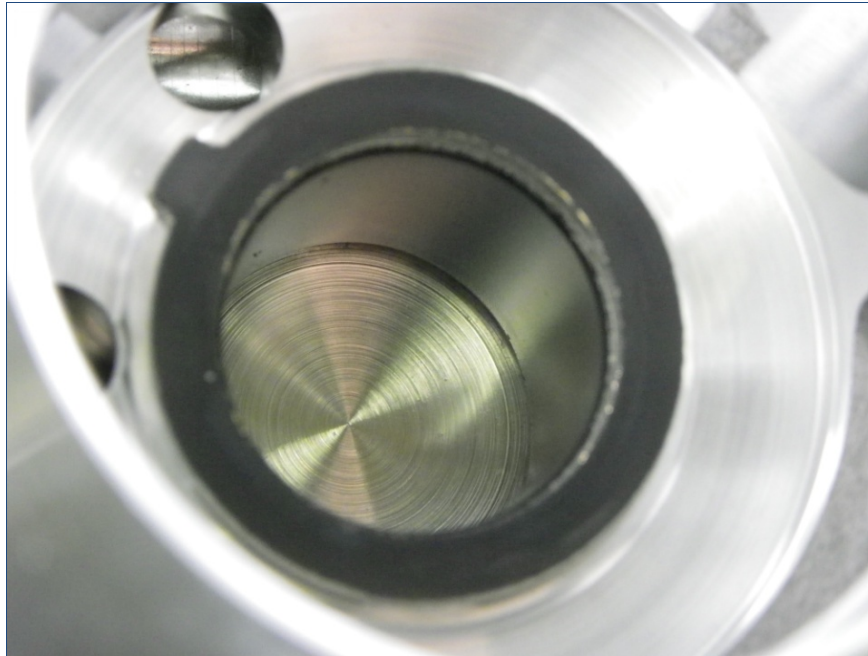


Figure 42. AF7938 50/50 JP-8/HRJ, Rear Pump Body Camshaft Bushing



Figure 43. AF7938 50/50 JP-8/HRJ, Front Pump Body Camshaft Bushing

Figure 44 shows the HPCR fuel injection pump camshaft for the JP-8/HRJ test. As was seen with the other military fuels previously tested, only light burnishing is present at the cam lobe/roller follower contact, and slight wear is seen at the contact location of the shaft seal.



Figure 44. AF7938 50/50 JP-8/HRJ, HPCR Pump Camshaft

Figure 45 shows a close-up of one of the cam lobe peaks, which is in very good condition with only light polish and light burnishing for the fuel lubricated, heavily loaded contact. As previously seen with the other military fuels, the light burnishing evident does not measurably alter the surface finish.

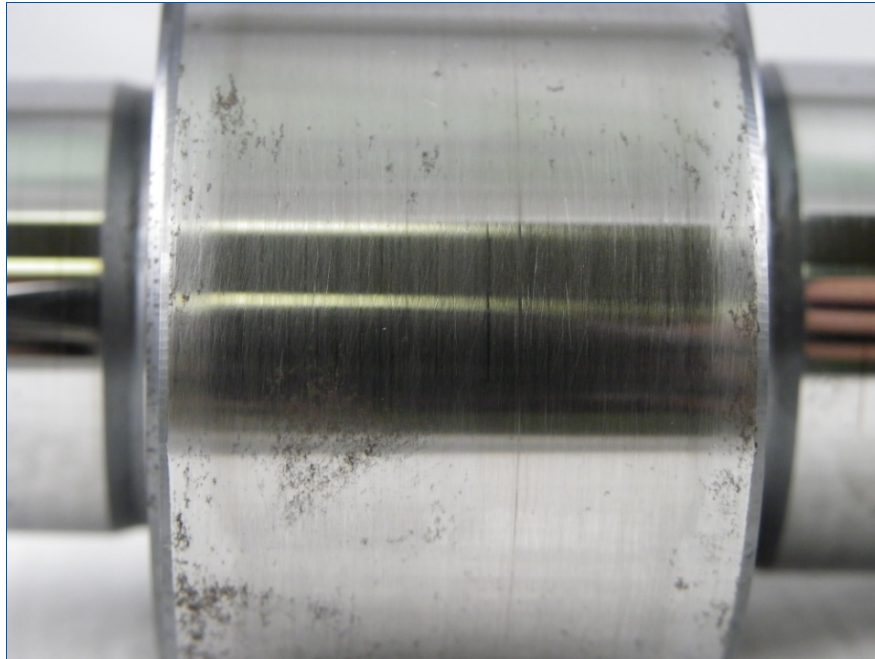


Figure 45. AF7938 50/50 JP-8/HRJ, HPCR Pump Camshaft, Lobe Surface Close-Up

(Note – Oxidation seen on surface was not present upon tear down of pump. Oxidation occurred during storage after completion of the test.)

4.1.10 Post Test Fuel Injection High Magnification Photos

Consistent with the high pressure fuel pump inspection, fuel injectors from the test were removed and disassembled for inspection and photographs. Due to the size of the fuel injectors internal components, many photos were taken under magnification to better determine any wear patterns present. Inspections were made to the hydraulic coupler pistons, control valve, control plates, injector needle, and nozzle.

Figure 46 shows the injector nozzle tip. No substantial deposit formations were seen under low magnification. Figure 47 below shows the injector needle tip. No abnormal wear, deposits, or markings were found on the tapered tip.

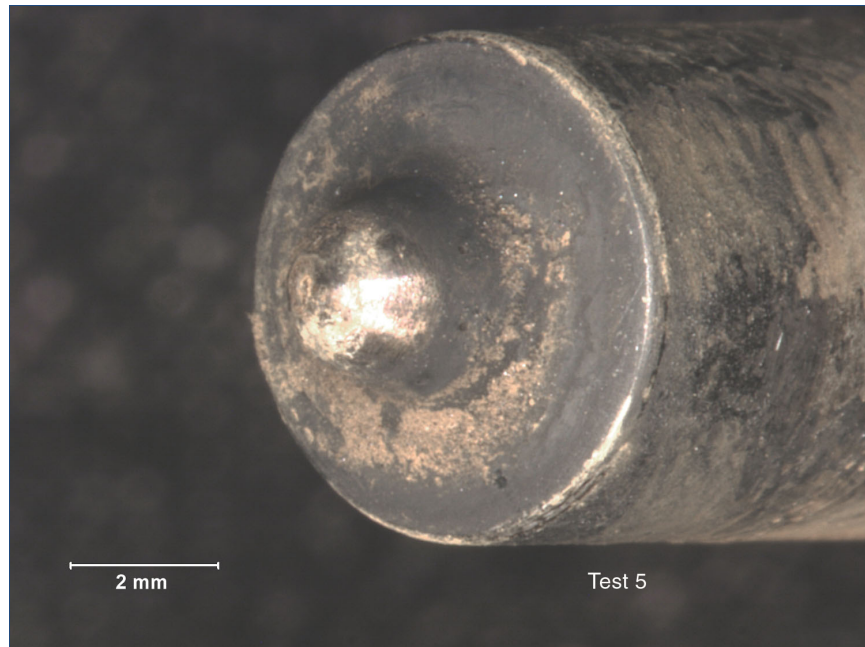


Figure 46. AF7938 50/50 JP-8/HRJ, Injector Nozzle

With the exception of slight deposition differences between the diesel and military fuels (primarily noticed in coloring), no other differing wear patterns could be identified between the previous ULSD and military fuels tests and the JP-8/HRJ fuel test. From the inspection, the only internal injector components showing any appreciable wear patterns were the upper pistons of the hydraulic coupling. As previously explained, the hydraulic coupler is used to translate the small linear movement of the piezoelectric-stack to a larger linear movement to operate the injector control valve and regulate needle lift. From the inspection, it appeared that the piezoelectric-stack imparted a slight side load on the upper piston causing a reacting wear scar to be formed on the outer piston surface. This wear scar was seen in each of the test fuels, and was found to be overall similar in size and condition between the ULSD and military fuels at 210-hours and the JP-8/HRJ at 420-hours.

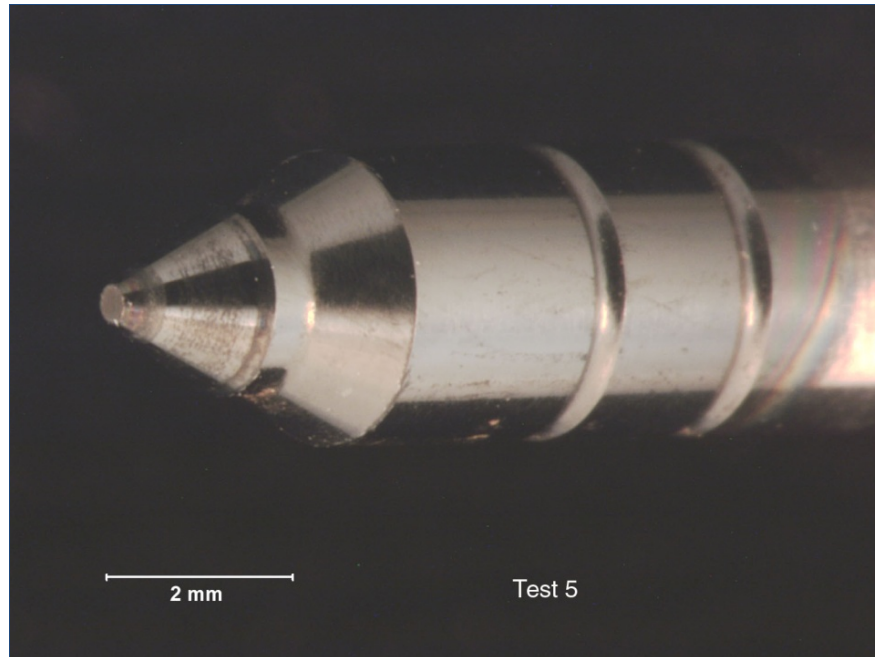


Figure 47. AF7938 50/50 JP-8/HRJ, Injector Needle

Figure 48 and Figure 49 show the side profile of the upper hydraulic coupler piston. A wear scar shows on the surface of the piston consistent with wear expected from being slightly cocked in the bore when depressed by the piezoelectric stack. Wear was seen at this location with the previous test fuels also.

Although this wear did not impact the testing at hand, this type of wear is typical of wear that can be detrimental to fuel injector function if continued. Binding or sticking of the hydraulic coupler will impair the action of the control valve which can potentially result in no fuel being injected into the engine, or a constant flow of injected fuel. Either of these occurring during engine operation would require immediate fuel injector replacement to ensure proper engine operation.

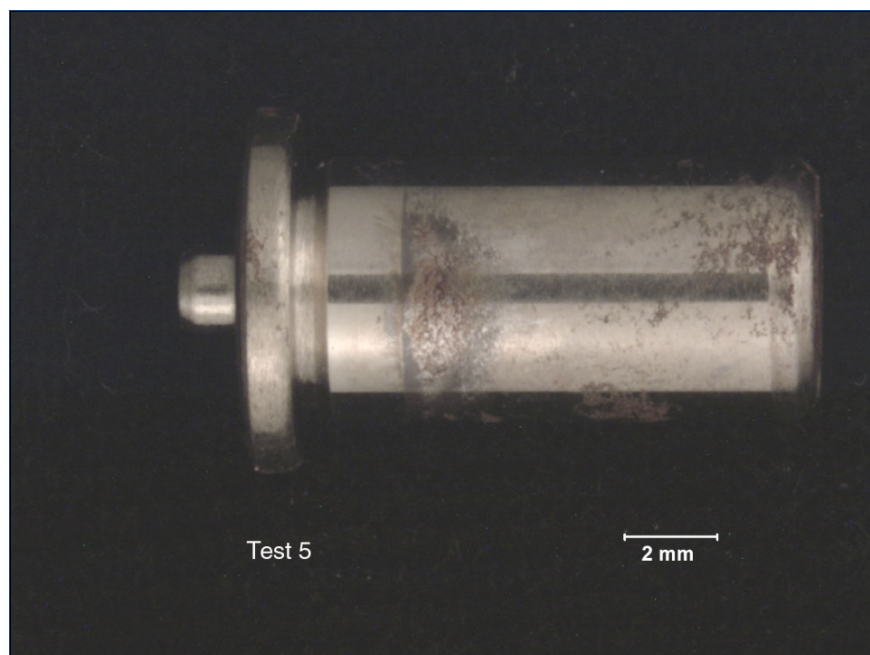


Figure 48. AF7938 50/50 JP-8/HRJ, Upper Hydraulic Coupler Piston, Profile

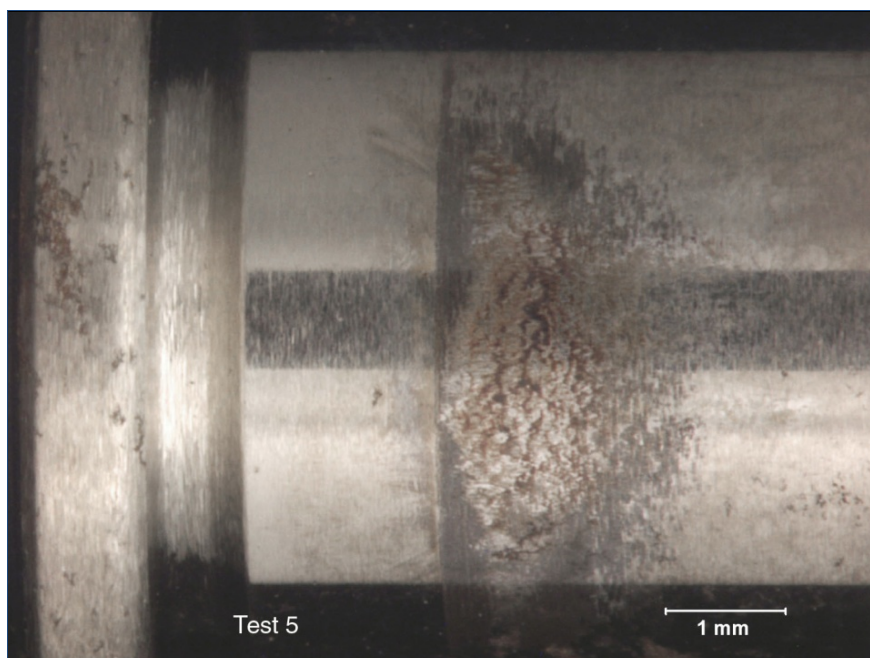


Figure 49. AF7938 50/50 JP-8/HRJ, Lower Hydraulic Coupler Piston, Wear Scar Close Up

Figure 50 and Figure 51 show the upper and lower hydraulic coupler pistons contact surfaces respectively. No noticeable wear was seen on the piston surface interface, or at the heads of the piston at the piezoelectric stack and control valve interface.

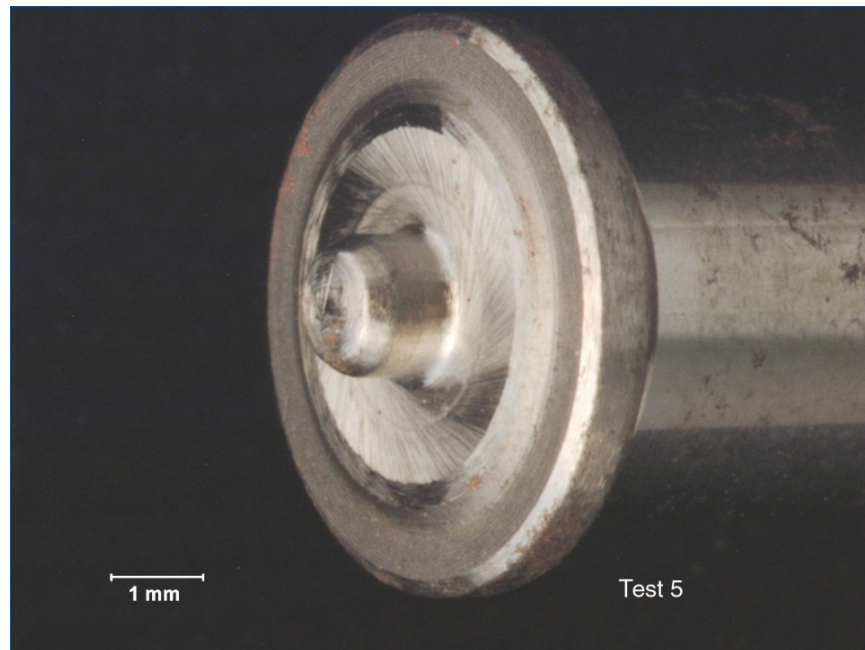


Figure 50. AF7938 50/50 JP-8/HRJ, Upper Hydraulic Coupler Piston

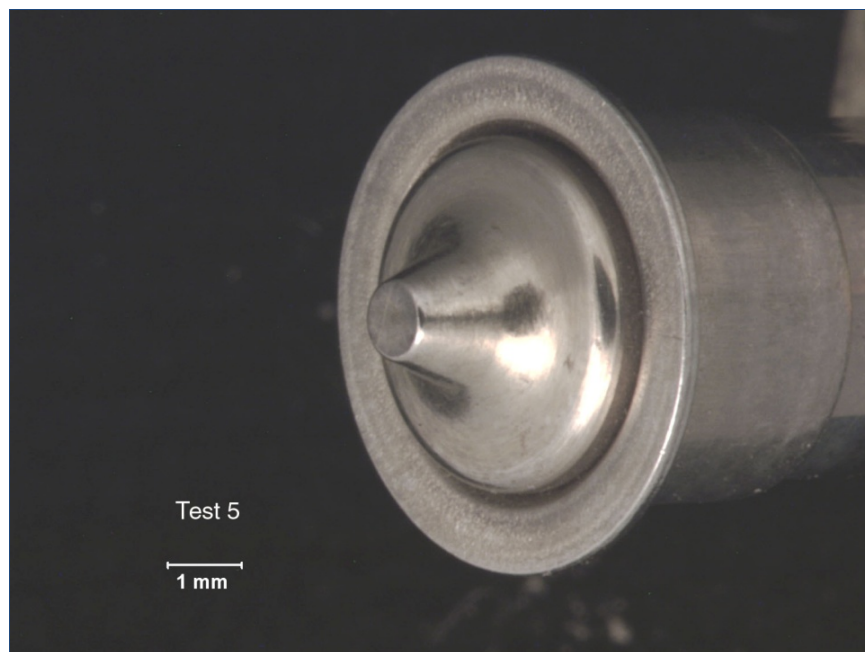


Figure 51. AF7938 50/50 JP-8/HRJ, Lower Hydraulic Coupler Piston

Figure 52 and Figure 53 show the top and bottom surfaces of the intermediate plate. This plate contains the fuel control passages used to manipulate the needle position.

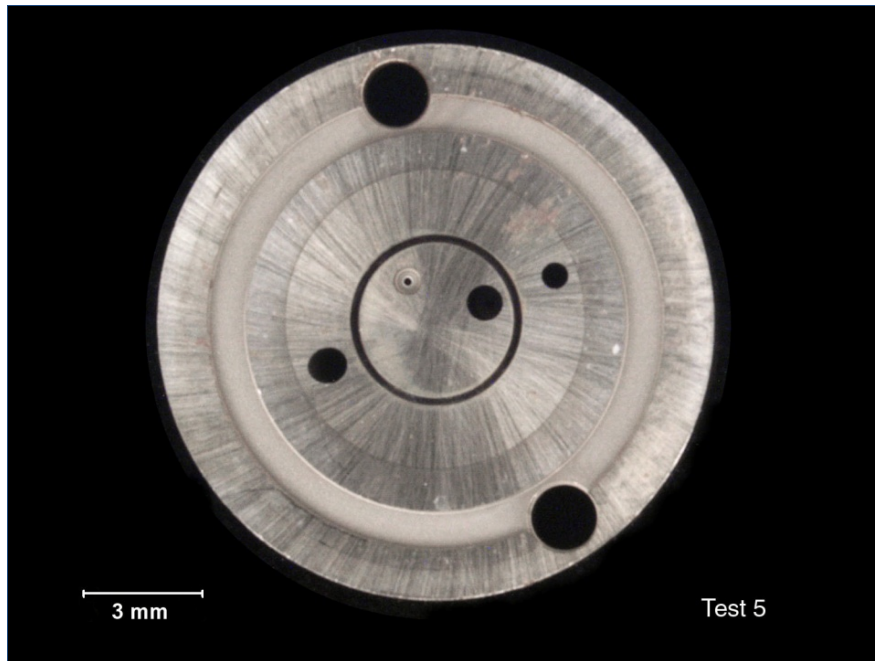


Figure 52. AF7938 50/50 JP-8/HRJ, Intermediate Plate (Top)

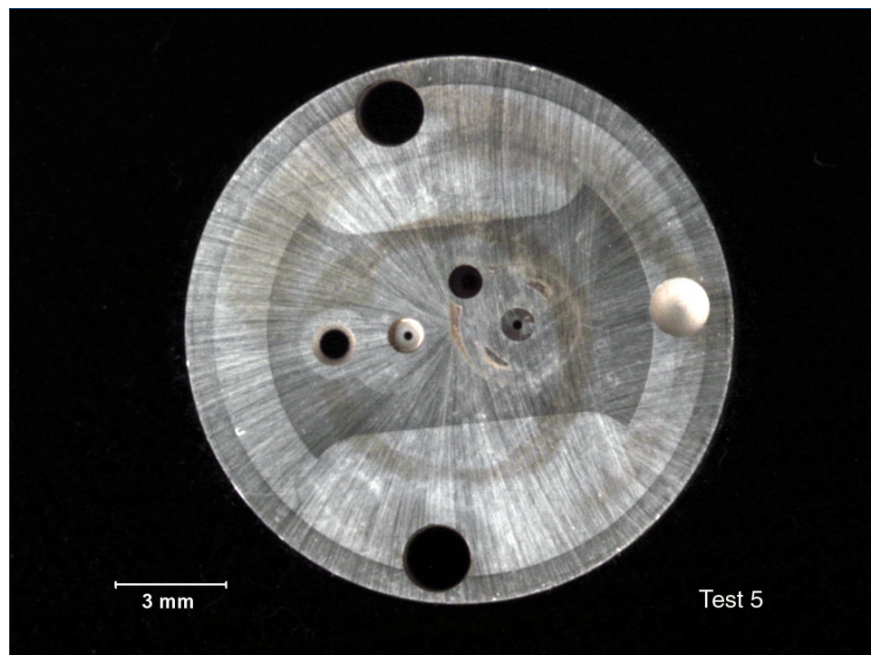


Figure 53. AF7938 50/50 JP-8/HRJ, Intermediate Plate (Bottom)

Figure 54 and Figure 55 show the top and bottom of the control valve plate, with light fuel deposition evident. The control valve sits in the bore shown in Figure 55. The lower piston of the hydraulic coupler operates in the bore shown in Figure 54.

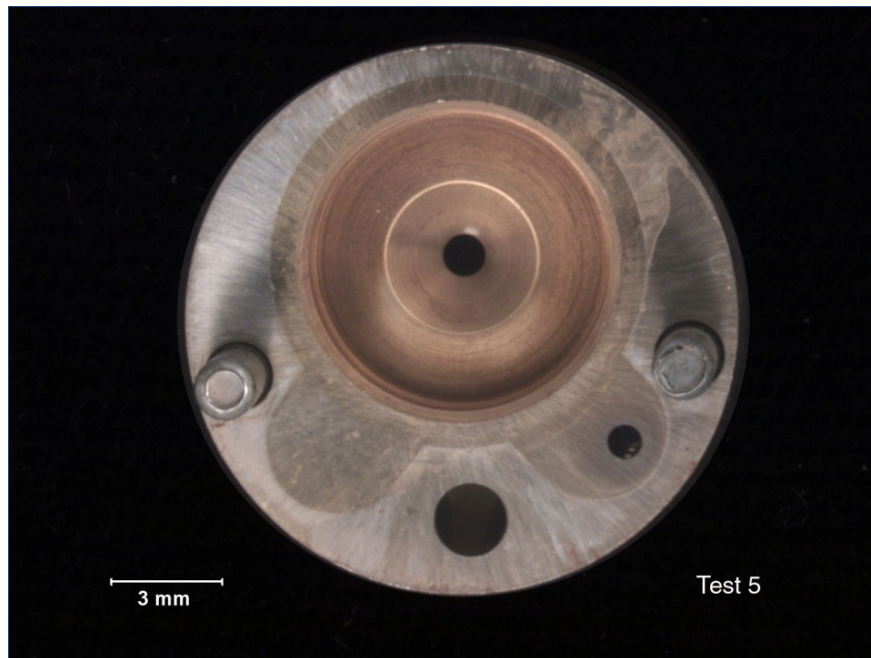


Figure 54. AF7938 50/50 JP-8/HRJ, Control Valve Plate (Top)

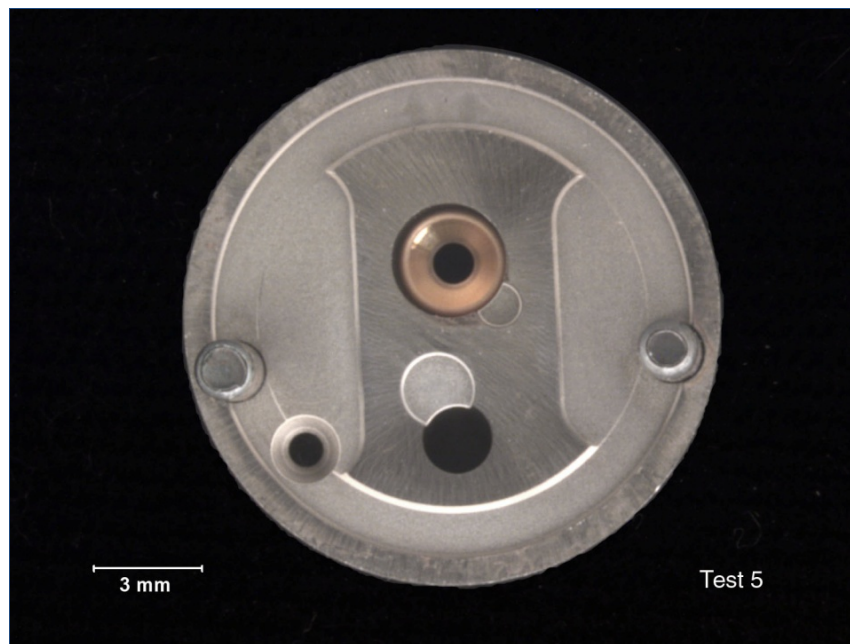


Figure 55. AF7938 50/50 JP-8/HRJ, Control Valve Plate (Bottom)

Figure 56 shows the control valve which regulates the pressure on top of the injector needle, thus controlling needle lift and injection timing. No unusual wear was found on the control valve.

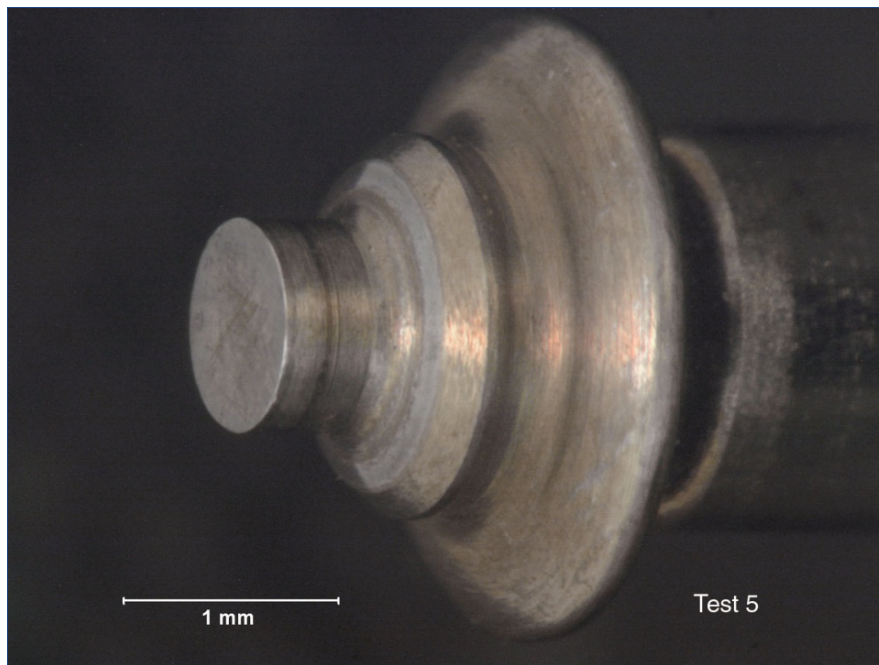


Figure 56. AF7938 50/50 JP-8/HRJ, Fuel Injector Control Valve

5.0 CONCLUSIONS

Testing conducted supports that the Ford 6.7L fuel lubricated high pressure common rail fuel injection system can be successfully operated using military specified fuels at normal ambient conditions, including a fuel blend of 50% JP-8/50%HRJ with 9ppm of a QPL-25017 additive. Even at the minimum lubricity enhancing treat rates, the tested JP-8/HRJ synthetic fuel blend provided adequate component protection and system performance compared to previous fuels testing. No unusual fuel related operating conditions were experienced throughout testing, and engine performance remained consistent and satisfactory throughout. Post test fuel injection system inspections found used components to be in similar condition throughout all tests (Table 13), for all fuels operated to date for U.S. Army and U.S. Air Force test fuel programs performed by SwRI in a Ford 6.7L engine (3), despite the large differences in fuel lubricity from the baseline to synthetic fuel tests, and for the double duration JP-8/HRJ fuel test.

6.0 RECOMMENDATIONS

Due to the minimal differences seen in component conditions at the end of testing, it is recommended that further testing be considered at more stringent conditions to ensure long term military fuel compatibility. An issue to investigate for military fuel compatibility would be testing at the double duration while operating at higher fuel inlet temperatures. It is unknown at this time whether wear patterns experienced during this testing could worsen to the point of causing operational problems, or will remain benign in terms of engine operation. Testing at elevated fuel inlet temperatures would be beneficial to determine if operation at desert like conditions would accelerate wear patterns in the fuel system. Ford/Bosch specifies that fuel inlet temperatures are to be maintained below 70°C (158°F) for use. Fuel temperature specifications experienced in desert operation have historically been difficult to accurately predict, but have the potential to elevate above recommended conditions. This could potentially have a dramatic impact on fuel system operation and compatibility.

7.0 REFERENCES

1. Development of Military Fuel/Lubricant/Engine Compatibility Test, CRC Report 406, January 1967.
2. Electronic Code of Federal Regulations, Title 40, Part 86, Subpart D, March 15, 2011.
3. Brandt, Adam; Yost, Douglas, "*Evaluation of Military Fuels using a Ford 6.7L Powerstroke Diesel Engine*", Interim Report TFLRF No. 415, August 2011, ADA560574.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

<u>Acronym</u>	<u>Description</u>
°	Degree
%	Percent
Al	Aluminum
AFR	Air/Fuel Ratio
AFRL	Air Force Research Laboratory
CN	Cetane Number
CO	Carbon Monoxide
COA	Certificate of Analysis
COEI	Carbon Monoxide Emissions Index
COTS	Commercial Off-The-Shelf
Cu	Copper
DFCM	Diesel Fuel Condition Module
DoD	Department of Defense
EGR	Exhaust Gas Recirculation
EI	Emissions Index
Fe	Iron
FIP	Fuel Injection Pumps
HC	Hydrocarbon
H/C	Hydrogen/Carbon atom ratio
HCEI	Hydrocarbon Emissions Index
HEFA	Hydroprocessed Esters and Fatty Acids
HPCR	High Pressure Common Rail
HofC	Heat of Combustion
HRJ	Hydroprocessed Renewable Jet
IQT	Ignition Quality Test
NO _x	Oxides of Nitrogen
PCM	Powertrain Control Module
PCV	Pressure Control Valve
Pb	Lead
ppm	Parts per Million
RQ (RZ)	Aerospace Systems Directorate (Propulsion Directorate)
RQP	Power Division
RQPF	Fuels & Energy Branch

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS *(Cont'd)*

<u>Acronym</u>	<u>Description</u>
SPK	Synthetic Paraffinic Kerosene
SwRI	Southwest Research Institute
TAN	Total Acid Number
TBN	Total Base Number
TWVC	Tactical Wheeled Vehicle Cycle
ULSD	Ultra Low Sulfur Diesel
UTC	Universal Technology Corporation
VCV	Volume Control Valve
WPAFB	Wright-Patterson Air Force Base